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FACILE FABRICATION OF MXENE/SIC-BASED ELECTROCHEMICAL INK ELECTRODES

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Abstract.

In this study, MXene/SiC-based conductive ink electrodes were successfully fabricated using a simple and low-cost direct writing method for potential electrochemical applications. The objective of this work was to develop a facile fabrication strategy for conductive composite ink by combining two-dimensional MXene nanosheets with silicon carbide (SiC) nanoparticles to improve the conductivity, structural stability, and adhesion of printed electrodes. MXene was synthesized by selective etching of the Ti_3AlC_2 MAX phase, and the obtained MXene nanosheets were mixed with SiC nanoparticles to prepare conductive ink. Chitosan solution was employed as a binder to enhance the adhesion and mechanical stability of the conductive coating on a polyvinyl chloride (PVC) substrate. The prepared conductive ink was manually deposited onto the PVC substrate using a direct writing technique and dried at room temperature.

The morphology and elemental composition of the fabricated electrodes were characterized by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The SEM images revealed a homogeneous distribution of MXene and SiC particles, while the EDS analysis confirmed the successful incorporation of Ti, C, Si, and other constituent elements into the composite electrode. The fabricated electrodes exhibited uniform film formation, good adhesion to the substrate, and favorable conductive characteristics, demonstrating the feasibility of the proposed fabrication method for conductive electrode preparation. These results indicate that the MXene/SiC composite ink is a promising material for the development of flexible and low-cost electrochemical electrodes. The proposed approach provides a simple, scalable, and cost-effective strategy for fabricating conductive electrodes with potential applications in electrochemical sensors, printed electronics, energy storage devices, and other flexible electronic systems.

Keywords: MXene, silicon carbide, conductive ink, electrochemical electrode, direct writing, nanocomposite, flexible electrode, chitosan.

1. Introduction

Recently, electrochemical electrodes based on nanomaterials have attracted significant attention due to their excellent electrical conductivity, large surface area, and promising electrochemical performance. Among various nanomaterials, MXene has emerged as a highly attractive two-dimensional material because of its unique layered structure, hydrophilicity, and superior electrical properties. In addition, silicon carbide (SiC) nanoparticles possess high chemical stability, mechanical strength, and thermal resistance, making them suitable for electrode fabrication. Conductive ink technology has become an important approach for the fabrication of flexible and portable electrochemical devices. Compared with conventional electrode preparation methods, direct writing techniques offer several advantages, including simplicity, low cost, and easy processing. Therefore, the development of MXene-based conductive ink electrodes is of considerable interest for future electrochemical applications[1].

In this study, MXene and SiC nanoparticles were used to prepare conductive electrochemical ink. The electrodes were fabricated on PVC substrates using a simple brush-writing method with chitosan as a binder. The morphology and electrochemical properties of the fabricated electrodes were

investigated to evaluate their potential application in electrochemical systems.

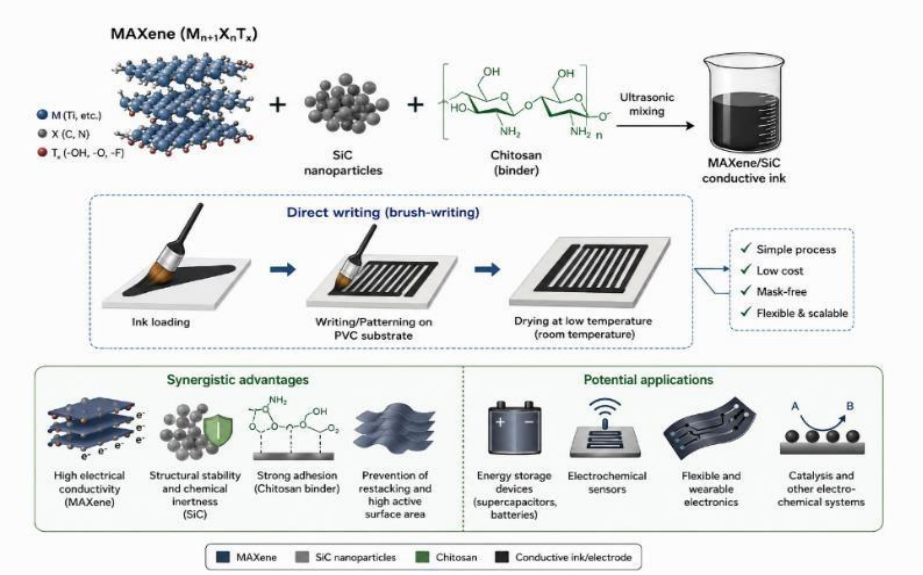


Figure 1 - Schematic illustration of MXene/SiC conductive ink preparation and brush-written electrode fabrication process

MXene is one of the new-generation nanomaterials with a two-dimensional structure. It belongs to the family of transition metal carbides, nitrides, and carbonitrides. Since its first discovery in 2011, MXene has attracted significant attention from researchers. The general formula of MXene is expressed as $M_n+1X_nT_x$, where M represents a transition metal, X refers to carbon and/or nitrogen, and Tx denotes surface functional groups such as -OH, -O, and –F [2]. The presence of these functional groups improves the hydrophilicity of MXene and allows it to disperse well in various solutions. In addition, the metallic layers provide excellent electrical conductivity. Due to its outstanding electrochemical, mechanical, electronic, and optical properties, MXene has been widely used in energy storage devices, sensors, electronics, biomedicine, and catalysis [3]. After the exfoliated layers are uniformly dispersed in solvents and mixed with additional components, functional inks suitable for printing can be obtained. Such inks make it possible to fabricate electrochemical devices using simple and efficient methods. In recent years, printing technologies have been widely applied in the development of energy storage systems due to their advantages, including simple fabrication process, low cost, and suitability for large-scale production[4]. Selecting an appropriate printing method is an important step in the fabrication of electrochemical devices. Different printing technologies vary in printing resolution, film thickness, and processing speed. Therefore, the properties of the prepared ink should be compatible with the selected printing technique. To improve the stability of the ink and ensure uniform deposition on the

substrate surface, various binders and additives are commonly introduced into the ink composition [5].

In addition, thermal treatment is often used to remove excess additives from the material. However, high-temperature processing may affect the material properties and complicate the fabrication procedure. For this reason, increasing attention has been focused on conductive inks that can be processed at low temperatures and easily deposited onto flexible substrates. Previous studies have reported that inks based on graphene, black phosphorus, molybdenum disulfide, and MXene exhibit promising performance on various substrates [6].

Silicon carbide (SiC) is another promising material that has attracted increasing attention in electrochemical and electronic applications due to its excellent thermal stability, high mechanical strength, chemical inertness, and semiconductor properties [7]. Compared with conventional carbon-based nanomaterials, SiC nanoparticles exhibit superior resistance to corrosion and oxidation, making

them suitable for harsh operating environments. In addition, the incorporation of SiC nanoparticles into conductive composites can improve structural stability and increase the active surface area of electrode materials. Owing to these advantages, SiC-based materials have been widely investigated in sensors, energy storage devices, catalytic systems, and electronic applications [8].

Recently, the combination of MXene with other nanomaterials has become an effective strategy to enhance the functional properties of conductive composites. In particular, hybrid materials based on MXene and ceramic nanoparticles demonstrate improved electrochemical stability and mechanical durability [9]. The layered structure of MXene provides efficient pathways for electron transport, while SiC nanoparticles can prevent the restacking of MXene sheets and maintain the accessibility of active sites. Therefore, the development of MXene/SiC composites is considered a promising approach for fabricating conductive inks and electrochemical electrodes[10].

Another important aspect in the fabrication of conductive inks is the selection of suitable binders and substrates. Chitosan has attracted attention as a biodegradable and environmentally friendly polymer due to its excellent film-forming ability and adhesive properties [11]. The presence of amino and hydroxyl functional groups in chitosan promotes strong interaction between the conductive material and the substrate surface. As a result, chitosan is widely used as a binder in electrochemical and printed electronic applications. Furthermore, flexible substrates such as polyethylene terephthalate (PET), paper, textiles, and polyvinyl chloride (PVC) are commonly employed for printed electrodes because of their low cost, lightweight nature, and mechanical flexibility [12].

Among various fabrication techniques, direct writing methods have emerged as simple and efficient approaches for producing flexible electrochemical devices. Unlike conventional lithographic and vacuum-based methods, brush writing does not require expensive equipment or complicated [13]processing steps. This method enables rapid deposition of conductive materials onto different substrates and allows the fabrication of customizable electrode patterns. In addition, direct writing techniques are compatible with large-area and low-temperature processing, which is important for flexible and wearable electronic systems [14].

Previous studies mainly focused on MXene-based inks for supercapacitors, microsupercapacitors, and printed electronics applications [15-17]. However, studies related to MXene/SiC-based conductive ink electrodes prepared by simple brush-writing methods are still limited. Therefore, developing low-cost conductive electrodes based on MXene and SiC nanoparticles remains an important research direction in the field of electrochemical materials.

In this work, MXene/SiC conductive ink was successfully prepared and applied for the fabrication of electrochemical electrodes on PVC substrates. The prepared materials were characterized using morphological analysis, and the feasibility of the fabricated conductive electrodes for electrochemical applications was evaluated. The proposed fabrication approach provides a simple and cost-effective strategy for the development of conductive materials for future printed and flexible electrochemical devices [18-19].

2. Materials and methods

2.1 Synthesis methods of MXene and ink formulation

To develop MXene-based electrochemical materials, MXene nanosheets were synthesized from the Ti_3AlC_2 MAX phase through selective chemical etching using hydrofluoric acid (HF). The synthesis process of MXene is illustrated in Figure 2. Briefly, 2.6 g of Ti_3AlC_2 powder was gradually added to 40 mL of 40 wt% HF solution in a Teflon reaction vessel under continuous stirring. The etching process was carried out at 35 °C for 10 h. During this process, the aluminum layers in the Ti_3AlC_2 MAX phase were selectively removed, resulting in the formation of two-dimensional $Ti_3C_2T_x$ MXene, where T_x represents surface functional groups such as –O, –OH, and –F.

After the etching process, the obtained black precipitate was repeatedly washed with distilled water by centrifugation until the pH of the supernatant reached 6–7. The purified product was then dried under vacuum at 40 °C, yielding 2.1 g of $Ti_3C_2T_x$ (MXene) powder.

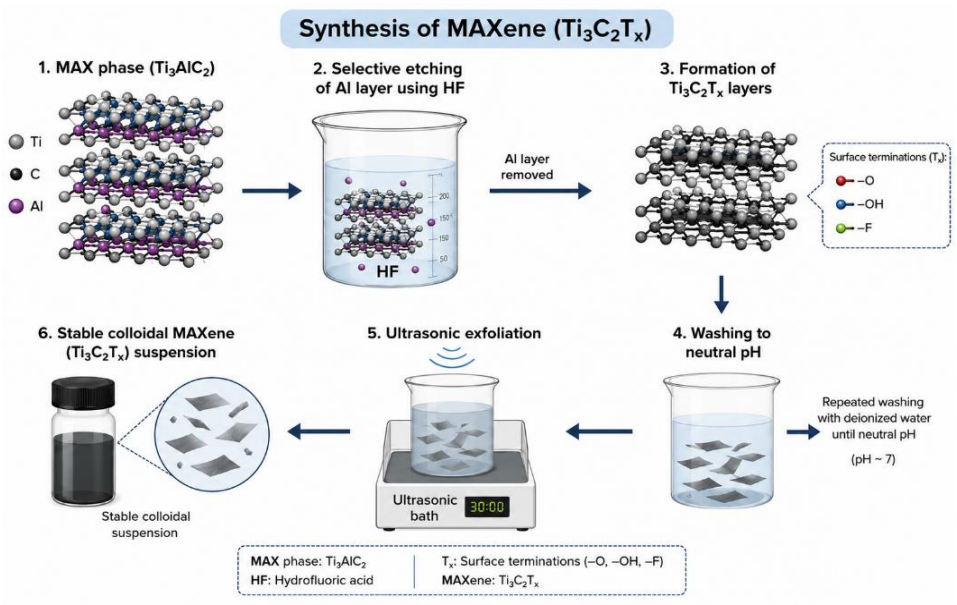


Figure 2 - Synthesis of MXene

The conductive electrochemical ink was prepared by mixing the synthesized MXene powder with SiC nanoparticles. Chitosan solution was used as a binder to improve the adhesion and mechanical stability of the conductive coating on the PVC substrate. The resulting homogeneous conductive ink was applied onto the PVC substrate using a direct writing technique and dried at room temperature. Finally, MXene/SiC-based conductive electrodes suitable for electrochemical applications were successfully fabricated.

2.2 Preparation of electrode ink

100 mg of SiC nanoparticles and 100 mg of MXene were dispersed in 10 mL of ultrapure water and ultrasonicated for 30 min to obtain the working electrode ink. Meanwhile, silver nanowires with a concentration of 20 mg/mL were dispersed in 10 mL of ultrapure water to prepare the reference/counter electrode ink. To ensure strong adhesion of the electrode materials onto the substrate surface, chitosan solution was used as a binder. For this purpose, 50 mg of chitosan was dissolved in 10 mL of 0.1 M acetic acid solution.

2.2 Preparation of electrochemical sensor

As shown in Figure 3, the working and reference/counter electrode inks, together with the chitosan solution, were sequentially written onto a solid substrate (such as PVC) using a brush. The prepared electrodes were then dried at room temperature for 20 min. Finally, the electrodes were cut into small pieces with dimensions of 3 mm × 3 mm for further use. The electrochemical system was based on a two-electrode configuration.

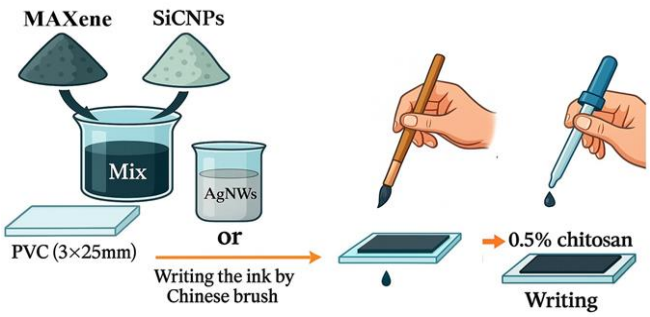


Figure 3 - Fabrication process of MXene/SiC NPs-CS and reference/counter electrode

The MXene/SiC-based conductive ink electrodes were successfully fabricated using the brush-writing method (Figure 4). The prepared electrodes formed a uniform coating layer on the PVC substrate and exhibited good mechanical stability. No visible cracks or delamination were observed on the electrode surface, indicating that the chitosan binder effectively improved the adhesion of the material onto the substrate surface. In addition, the compact size and simple fabrication process of the obtained electrodes demonstrate their potential applicability in electrochemical devices.

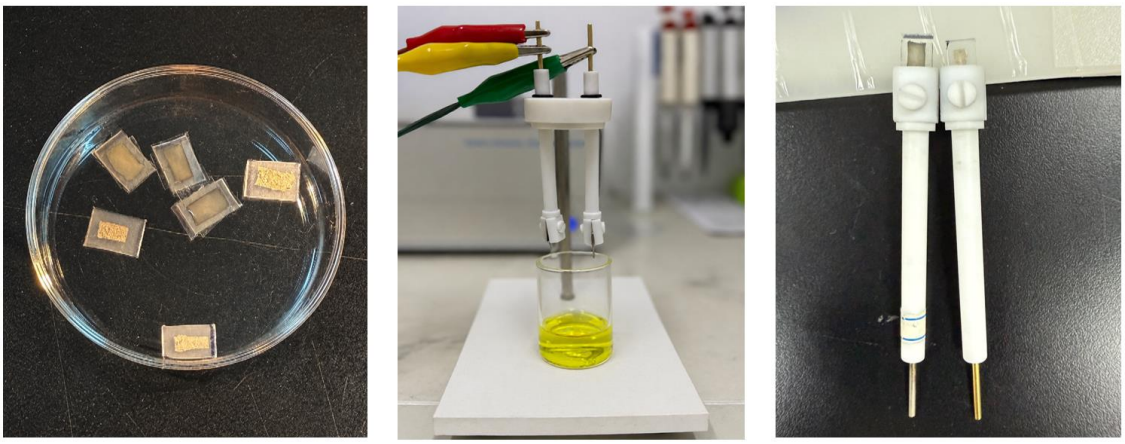
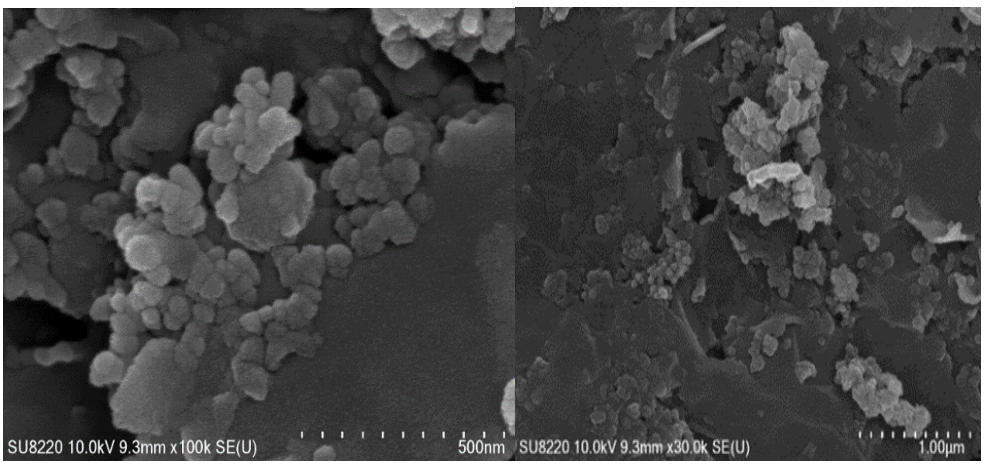


Figure 4 - Fabricated MXene/SiC-based conductive ink electrodes

3. Results and discussion

The SEM images show the morphology of the synthesized MXene/SiC composite material. The obtained images reveal the structural features and surface morphology of the composite. A layered and sheet-like structure characteristic of MXene can be clearly observed. The interconnected layered morphology confirms the two-dimensional nature of the MXene material. In addition, granular particles with different sizes are distributed on the surface, indicating the successful incorporation of SiC nanoparticles onto the MXene sheets.

According to the SEM results, the surface of the composite exhibits a rough and relatively developed morphology (Figure 5). Such a structure can contribute to an increased specific surface area of the material. Furthermore, the SiC nanoparticles located between the MXene layers may reduce the restacking of the sheets, which can positively influence the stability and conductivity of the composite. The higher magnification SEM image demonstrates that the SiC nanoparticles are distributed on the surface and between the layers of the MXene sheets. The relatively uniform distribution of the particles confirms the successful synthesis of the MXene/SiC composite. The absence of large agglomerates suggests that the synthesis process was carried out effectively.



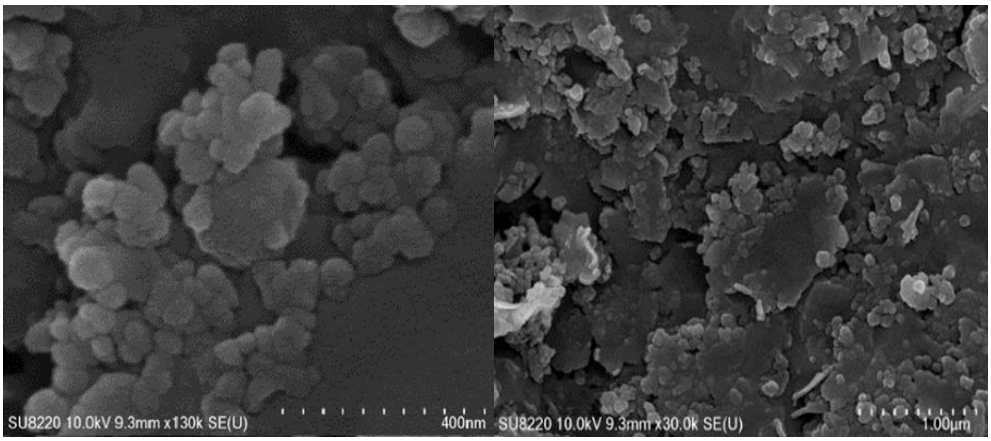


Figure 5 - SEM characterization of the synthesized MXene/SiC nanocomposite structure

Overall, the SEM analysis indicates that the MXene/SiC composite possesses a layered structure with well-dispersed SiC nanoparticles interacting with the MXene surface. Such structural characteristics make the material promising for electrochemical applications.

The synthesized MXene material was successfully obtained by selective etching of the Al layer from the Ti_3 AlC_2 MAX phase using HF solution. After the etching process and ultrasonic treatment, a stable MXene suspension was formed, indicating the successful delamination of the layered structure. The obtained MXene exhibited good dispersibility in aqueous solution due to the presence of surface functional groups. The morphology and surface structure of the synthesized MXene/SiC composite were investigated using SEM analysis. As shown in Figure 4, the material exhibited a typical layered and sheet-like structure characteristic of MXene. The SEM images also revealed that the SiC nanoparticles were distributed on the surface and between the MXene layers. The incorporation of SiC nanoparticles contributed to the formation of a rough and developed surface morphology, which may enhance the active surface area of the material.

In addition, the layered MXene structure provided conductive pathways for electron transfer, while the SiC nanoparticles could improve the structural stability of the composite. The relatively uniform distribution of SiC particles on the MXene sheets indicates the successful formation of the MXene/SiC nanocomposite. No significant agglomeration was observed in the SEM images, suggesting that the synthesis and dispersion processes were effective. The prepared MXene/SiC conductive ink showed good adhesion to the PVC substrate with the assistance of chitosan binder. The brush-writing method allowed the facile fabrication of electrochemical electrodes with a relatively uniform coating layer. After drying at room temperature, the fabricated electrodes maintained good structural integrity without visible cracks on the surface. Overall, the obtained results demonstrate that the MXene/SiC composite is a promising material for conductive ink and electrochemical electrode fabrication. The simple preparation procedure and favorable structural properties indicate its potential application in future electrochemical devices and flexible electronic systems.

4. Conclusion

In this work, a MXene/SiC-based conductive composite was successfully prepared, and its potential application as an electrochemical ink was investigated. The layered structure of MXene together with the stability of SiC nanoparticles contributed to the improvement of the functional properties of the composite. In addition, the use of chitosan as a binder provided good adhesion of the material onto the substrate surface. The proposed brush-writing method demonstrated a simple and accessible approach that does not require complex equipment. Using this method, electrochemical electrodes can be fabricated in a short period of time. The structural characteristics of the prepared materials indicate their suitability for electrochemical applications.

Overall, MXene/SiC-based conductive inks represent a promising direction for the fabrication of electrochemical materials. In the future, such materials may find potential applications in sensor platforms, flexible electronics, and printed technologies.

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