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MXene framework-supported F, S, and Co ternary-doped tin dioxide hybrid structures for ultrafast and stable lithiumion batteries

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Summary

Owing to the increasing requirements of electronic devices, lithium-ion batteries (LIBs) have emerged as a potential energy storage medium. However, given the limitations of pure graphite, it is crucial to develop anode materials for ultrafast LIB applications. Recently, the study of MXenes in energy storage fields has developed rapidly owing to their numerously distinct advantages for energy storage, including high electrical conductivity, high specific surface area, and high wettability. In this study, we first present the $Ti_3C_2T_x$ MXene framework-supported F, S, and Co ternary-doped tin dioxide hybrid structure (MXene-FCTOS) using an ultrasonic spray pyrolysis deposition process followed by the dopant-evaporation method. The resulting MXene-FCTOS exhibited notable energy storage performance, including high specific capacity (473.24 mAh/g at a current density of 100 mA/g) with superior ultrafast energy storage performance (125.25 mAh/g at 3000 mA/g). Hence, we believe that the MXene-FCTOS exhibits sufficient potential for realizing a competitive material for ultrafast LIB anodes.

K E Y W O R D S

anode, Li-ion battery, ternary-doped hybrid structure, ${\rm Ti}_3{\rm C}_2{\rm T}_{\rm x}$ MXene, ultrafast energy storage

1 | INTRODUCTION

The widespread usage of portable-sized electronic devices and large-sized energy storage mediums directly influences our daily lives.¹ The applications of modern electronic devices have necessitated the acceleration of the development of lithium-ion batteries (LIBs)² as essential energy storage components.³ Initially, LIBs attracted global attention for their high energy density, high cyclability, environmental friendliness, and affordability.⁴ However, with the advent of state-of-the-art electronic devices that consume considerable amounts of electrical energy or require a sustained operation, LIBs face several limitations such as poor cyclability, insufficient energy density, and low charging speed. Typically, conventional LIBs comprise five functional components: anode, cathode, separator, electrolyte, and external material. Among these, the energy storage performance is primarily affected by Liion insertion/desertion kinetics of the anode and cathode materials during charging and discharging. In particular, the anode materials affect the energy storage performance under high current density (ultrafast) charging and discharging conditions, including cyclability, specific capacity, and rate capability.⁵ Currently, anode materials including metals,⁶ transition metal oxides,⁷ and other compounds⁸ have been suggested as substitutes for pure graphite due to their low theoretical capacity (372 mAh/g) and poor ion diffusion kinetics.⁹

Recently, two-dimensional (2D) transition metal compounds called the MAX phase with an $M_{n+1}AX_n$ formula have attracted significant interest. M refers to the transition metal elements (Nb, Ti, V, etc.), A refers to the elements of groups 13-16 (Al, Si, Ge, Sn, etc.), and X refers to either C or N (n = 1-3).¹⁰ The multi-layered 2D MXene structure $(M_{n+1}X_nT_x)$ can be formed following the exfoliation process of the 'A' layer with several etchants, where T_x corresponds to the etchant-relevant surface groups including OH, O, and F. An etchant-induced sonication process can exfoliate the multi-layered structure into a few layers of MXene flakes. The study of MXenes in energy storage fields has developed rapidly because of the pioneering reports published by the Gogotsi group¹¹ involving several innovative research groups.¹² The MXene structure has various advantages for energy storage, including a high electrical conductivity (in the order of 10³ S/cm) and high wettability with hydrophilic surface functional groups. Owing to such unique characteristics, certain classes of MXenes were utilised for various research fields, including supercapacitors, sensors, water purification, and Li/Na-ion batteries. The MXene phase with Ti and C is renowned for its simple synthetic method and well-investigated etching mechanism with theoretical studies.¹³ In particular, the $Ti_3C_2T_x$ phase retains superior electrical conductivity while exhibiting excellent cation intercalation capability.¹⁴ Therefore, $Ti_3C_2T_x$ MXene could substitute pure graphite as a competitive anode material. However, ion insertion between the MXene sheets is naturally restricted due to surface T_x groups, which leads to the inferior specific capacities of Ti₃C₂T_x MXenes below 200 mAh/g.¹⁵ Therefore, proper modification and material designs are required to demonstrate the potential of Ti₃C₂T_x MXene as a competitive anode material. As a powerful modification strategy for active materials, the development of hybrid structures can effectively enhance the characteristics of conventional materials with physical, chemical, or electrochemical limitations. Recently, researchers have attempted to introduce high-capacity materials (Si, SnO₂, Fe₂O₃, etc.) to construct hybrid structures that can increase the capacity of MXenes. Among them, SnO₂ (tin dioxide) has received considerable interest as a composite material with MXene, primarily owing to its high theoretical capacity, affordability, and low Li-ion insertion voltage.¹⁶ However, it presents several problems, such as an inferior energy storage capability under ultrafast reaction conditions and poor cyclability during repetitive charging/ discharging reactions. The limitations primarily originate from its large volume change due to Li-ion insertion and low electrical conductivity. A heteroatom doping strategy has been suggested for enhancing the electrical conductivity of tin dioxide and relaxing the lattice stress during

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the volume change as a means of overcoming the existing limitations. For example, Koo et al reported an F-doped tin dioxide-coated carbon nanofiber with an external nanocarbon layer for LIB anode materials, which demonstrated good lithium storage capability under ultrafast charging/discharging conditions with high cyclability up to 500 cycles.¹⁷ However, the effect of co-doped or ternary-doped tin dioxide on the MXene framework for energy storage performance has not yet been established. In particular, multi-dopants can induce the synergistic effect depending on their role within the doping site to significantly enhance either the electrical or chemical characteristics. Thus, exploring various types of multidopant anode materials and demonstrating their synergistic effect is crucial for overcoming the limitation of existing research strategies.

In this study, we first report the $Ti_3C_2T_x$ MXene framework-supported F, S, and Co ternary-doped tin dioxide hybrid structure (MXene-FCTOS) for ultrafast and stable LIB applications. We successfully coated F, S, and Co ternary-doped tin dioxide onto the MXene framework by adopting the ultrasonic spray pyrolysis deposition (USPD) and following the dopant-evaporation process. Consequently, F, S, and Co dopants successfully enhanced the electrical conductivity of tin dioxide, increased the layer distance of Ti₃C₂T_x MXene, and stabilised the tin dioxide structure during reactions. Moreover, the MXene framework can suppress excessive volume changes in FCTOS. The fabricated MXene-FCTOS anode exhibited high specific capacity, excellent cyclability, and superior energy storage performance under ultrafast charging/discharging conditions. Therefore, MXene-FCTOS with a ternary-doped strategy can open a new chapter for developing competitive anode materials for ultrafast LIBs.

2 **EXPERIMENTAL DETAILS**

The MXene-FCTOS hybrid structure were successfully synthesised via a USPD process followed by the dopantevaporation method. First, 5 g of Ti₂AlC (99.9%, Nanografi) and 2.22 g of TiC (99.5%, Alfa Aesar) were mixed homogeneously and heated to 1450°C with Ar flow to obtain a Ti₃AlC₂ MAX structure. Subsequently, the Ti_3AlC_2 powder was etched with HF (50%, Duksan) in a sonication chamber to remove the Al interlayer and delaminate the mixture into MXene flakes. Following exfoliation, the resulting powder was dried at 50°C in an oven to prepare the $Ti_3C_2T_x$ MXene framework. Second, the F and Co co-doped tin dioxide (FCTO) was uniformly coated onto the MXene framework using the USPD process. For the USPD process, the precursor solutions were

prepared using 0.5 M SnCl₄·5H₂O (98%, Samchun), 0.2 M CoCl₂·6H₂O (98%, Alfa Aesar), 1.2 M NH₄F (99.5%, Aldrich), and 5 vol% of ethanol. Thereafter, the precursor solution was sprayed using a 1.6 MHz ultrasonic nebuliser and transported to the pyrolysis chamber by the N₂ flow gas. During the USPD process, the pyrolysis chamber was maintained at 350°C with a rotated sample holder to achieve a uniform FCTO coating on the MXene surface. The deposition time of the USPD process was adjusted by 20, 40, and 60 minutes, respectively, to optimize the loading amount of FCTO. Finally, the FCTO-coated MXene powder was placed in an alumina boat with the S dopant and heated to 600°C for the dopant-evaporation process. The S dopant evaporated at temperatures above 450°C and reacted with the surface FCTO particles, forming the FCTOS hybrid structure with the MXene framework. Accordingly, we synthesised three types of anode materials for comparison: bare Ti₃C₂T_x MXene, FCTO-coated MXene, and FCTOS-coated MXene (denoted as MXene, MXene-FCTO, and MXene-FCTOS, respectively).

Furthermore, the surface morphology and particle sizes were investigated using electron microscopy (FESEM, Hitachi SU8010). Moreover, the detailed internal structures of all the samples were verified using transmission electron microscopy (TEM, JEOL JEM-2100F). The chemical bonds and crystal structure were investigated using X-ray photoelectron spectroscopy (XPS, K-ALPHA⁺) and X-ray diffractometry (XRD, PANalytical-X'Pert Pro MPD) at the Centre for Research Facilities at Chonnam National University. Each synthesised sample was fabricated as an anode to demonstrate the electrochemical characteristics. The prepared slurries (ratio of 7:1:2 for active materials, conductive material, and binder, respectively) were dried at 100°C in an oven after being loaded onto an 18 µm Cu foil using a bar coater (Wellcos, MC-20). The active material loading masses of the respective electrodes were maintained at approximately 2 mg to minimise errors during the measurement of electrochemical characteristics. Coin cells (CR2032, Hohsen Corp.) comprise the fabricated electrodes, Li (Honjo, 99.999%), and 1.6 M LiPF₆ with EC: DEC (7:3) solvent for the working electrodes, counter electrodes, and electrolyte, respectively. Electrochemical impedance spectroscopy (EIS, the frequency range of 10^5 - 10^{-2} Hz) was performed to characterize the kinetic property. The energy storage capability was measured using a battery charging/discharging cycler (WonATech, WMPG 3000).

3 | RESULTS AND DISCUSSION

We synthesised a $Ti_3C_2T_x$ MXene-FCTOS by adopting the USPD process followed by the dopant-evaporation method. Figure 1 illustrates the fabricating process for the MXene, MXene-FCTO, and MXene-FCTOS samples. As shown in Figure 1A, the MXene sample was obtained by delaminating the TI_3AlC_2 layers using sonication. The structure consisted of multi-layered $Ti_3C_2T_x$ MXene sheets. Figure 1B displays the MXene-FCTO fabricated via USPD. During the USPD process, precursor droplets were generated from the ultrasonic atomiser. These



FIGURE 1 (A) Schematic illustration of the synthetic procedure for the hybrid structure of (A) MXene, (B) MXene-FCTO, and (C) MXene-FCTOS, respectively

precursor droplets were transported to the heated $(350^{\circ}C)$ chamber by the N₂ flow. As the transported droplets got closer to the chamber, solvent evaporation, solute condensation, and pyrolysis occurred sequentially, eventually forming the FCTO particles on the MXene surface.¹⁸ The FCTO particles were uniformly coated on the MXene framework using the rotating sample holder and the horizontally supplied precursor droplets. The dopantevaporation method was conducted in succession in a 600°C tube furnace with an S precursor to realise the MXene-FCTOS hybrid structure. During this process, the S dopant evaporated at temperatures greater than 450°C, and the surface reaction of the FCTO can be induced by vapour-phase sulphur.¹⁹ Remarkably, the growth of the FCTO particles also proceeded with the generation of the FCTOS structure, which increased the layer distance between the MXene sheets. Accordingly, the F, S, and Co ternary-doped tin dioxide structure with the expanded MXene framework could enhance the energy storage capability, particularly at a high current density owing to the improved electrical property and enhanced ionic transport kinetics.

Figure 2A-D illustrate the FESEM results for MXene, MXene-FCTO, and MXene-FCTOS samples, respectively. The MXene sample exhibiting a multi-layered structure with a smooth 2D surface morphology was identified. All the samples exhibited analogous particle sizes from 2 to 5 μ m, corresponding to the Ti₃C₂T_x MXene structure. Figure 2B illustrates uniformly coated FCTO particles on the MXene surface through a USPD process, in which the particle sizes are distributed from \sim 24.2 nm to \sim 57.2 nm.



FIGURE 2 FESEM images of (A) MXene, (B) MXene-FCTO, and (C,D) MXene-FCTOS

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The loading amount of FCTO was adjusted by 20, 40, and 60 minutes (referred to as MXene-FCTO20, MXene-FCTO40, and MXene-FCTO60). Consequently, MXene-FCTO40 exhibited an optimised hybrid structure, which was selected for the MXene-FCTO sample (see Figure S1). The advantages of a high electrical conductivity for $Ti_3C_2T_x$ MXene and a high specific capacity for tin dioxide can be achieved by developing the hybrid structure. Figure 2C,D confirm the growth of the FCTOS particle sizes (from \sim 72.4 to \sim 105.1 nm) accompanied by the expansion of layer distance. The ranges of the 2D MXene sheet spacing for the samples were measured to be \sim 5.3 to \sim 20.5 nm for MXene, \sim 12.1 to 32.4 nm for MXene-FCTO, and \sim 41.3 to \sim 84.7 nm for MXene-FCTOS. The expanded layer distance significantly contributes to the specific surface area enhancement and Li-ion transfer acceleration to the active sites of $Ti_3C_2T_x$ MXene and tin dioxide.

Low- and high-resolution TEM analyses were conducted (see Figure 3) to investigate the inner particle distribution and morphology in detail. Figure 3A,D illustrate the uniform contrast of TEM images for the MXene sample without any composite materials, with a lattice distance of 0.98 nm, signifying the $Ti_3C_2T_x$ (002) plane.²⁰ The MXene-FCTO illustrates the composite structure of the FCTO and MXene frameworks (see Figure 3B,E). At the surface region of the sample, the observed particle exhibited a 0.334 nm lattice constant, confirming the (110) plane of SnO_2^{21} Owing to the similar ionic radius of Sn^{4+} (0.069 nm) with Co²⁺ (0.066 nm) and O²⁻ (0.126 nm) with F^- (0.119 nm), we expect the FCTO particles to maintain the same lattice distance as in tin dioxide. However, with the large ionic radius of S^{2-} (0.170 nm), FCTOS exhibited an expanded lattice distance of 0.351 nm (see Figure 3C,F). Live profile data of TEM images, obtained from MXene-FCTO and MXene-FCTOS, were utilised (see Figure S2) to avoid the error during the measurement of lattice distance. They could contribute to increasing the Li-ion diffusivity with an enlarged ion transport pathway, providing superior ultrafast Li-ion storage capability. Moreover, the EDS mapping image of MXene-FCTOS was investigated to analyse the atomic distribution, which also exhibited a uniform distribution of the existing elements (Ti, C, O, S, F, Sn, and Co) (see Figure 3G).

Figure 4 illustrates the XRD data of MXene, MXene-FCTO, and MXene-FCTOS, which commonly possess a diffraction peak at approximately 9.2°, signifying the (002) plane of the $Ti_3C_2T_x$ MXene phase.²² MXene exhibits a relatively weak characteristic peak compared with tin dioxide, which can be attributed to the exfoliation process with HF. Interestingly, owing to the delamination process during etching, the peak position of the (002) plane was shifted when compared with that of a conventional Ti₃AlC₂ structure (JCPDS card #52-0875),



FIGURE 3 TEM image of (A,D) MXene, (B,E) MXene-FCTO, (C,F) MXene-FCTOS, and (G) EDS mapping results from the MXene-FCTOS



FIGURE 4 XRD curves obtained from all the samples

indicating the increased layer distance of MXene following the exfoliation process.¹¹ For MXene-FCTO, characteristic diffraction peaks were observed at ~25.23°, ~37.86°, and ~48.00°, corresponding to the (110), (200), and (211) planes of SnO₂, respectively.²³ MXene-FCTOS also exhibit characteristic peaks similar to those of MXene-FCTO, considering the overall peak intensity enhancement owing to the heat treatment during the dopant-evaporation process. The peak shift of the (110) plane occurred at a lower degree, confirming the increment in the lattice distance.

XPS analyses were performed to demonstrate the detailed structure and chemical bonding of the samples. Figure 5 displays the organised XPS data, which were fitted according to the reference carbon peak position. Figure 5A illustrates the Ti 2p spectra, confirming common peaks at \sim 460.8 and 455.1 eV, corresponding to the binding energies of the Ti-C and Ti-O_xF_v bonds, respectively.²⁴ Moreover, the Ti bonding signifies the successful formation of the $Ti_3C_2T_x$ MXene phase, which maintains its structure after the USPD and dopant-evaporation processes. In Figure 5B, MXene exhibits a strong single peak of Ti-F bonding originating from the intercalated T_x during the Al etching process with HF; the peak can be observed at approximately 685 eV. An excessive number of T_x groups at the interface of the MXene sheets obstruct the Li-ion diffusion kinetics and partially occupy the

FIGURE 5 XRD curves and XPS core-level spectra of (A) Ti 2p, (B) F 1s, (C) Co 2p, and (D) S 2p obtained from MXene, MXene-FCTO, and MXene-FCTOS



charge-storage sites, which can reduce the energy storage capability. Therefore, it is imperative to eliminate the excessive surface T_x groups to achieve superior energy storage performance with the MXene group materials. In this stream, MXene-FCTO and MXene-FCTOS samples exhibit a lower Ti-F bonding intensity with an additional peak at approximately 684.3 eV attributed to the SnO₂-F bonding. The FCTO and FCTOS particles, surface-coated by the USPD process, successfully eliminated the excessive T_x and generated SnO₂-F bonding.²⁵ Moreover, F⁻ substitutes the oxygen bonding site providing extra charge carriers to the lattice, which is crucial for increasing the electrical conductivity and subsequent ultrafast Li-ion storage performance.²⁶ Figure 5C depicts the Co 2p XPS spectra obtained from MXene, MXene-FCTO, and MXene-FCTOS. The MXene sample did not exhibit any peaks; however, the MXene-FCTO and MXene-FCTOS samples presented two peaks at approximately 797.1 eV for the Co $2p_{1/2}$ bonding and 780.0 eV for the Co $2p_{3/2}$ bonding. Hence, we confirmed that Co doping occurred for the MXene-FCTO and MXene-FCTOS samples. Moreover, Co can bond with Sn to form a Co-Sn intermetallic phase, which can increase the structural stability and cyclability of tin dioxide.²⁷ Furthermore, Co dopants can enhance the electrical conductivity of tin dioxide by promoting electron mobility. Figure 5D shows the S 2p XPS spectra for all the samples. It is clear that only the MXene-FCTOS sample exhibits two peaks at approximately 163.2 and 161.3 eV, which imply the S $2p_{1/2}$ bonding and S $2p_{3/2}$ bonding.²⁸ For comparing the

intensity of all chemical bonds, wide-range XPS data from 100 to 900 eV were also shown in Figure 3S. Thus, successful S doping into the FCTO structure was confirmed using the dopant-evaporation method. Moreover, additional space can be achieved in the tin dioxide structure through S doping because of the larger ionic radius of S (0.170 nm) than that of O. Accordingly, the Li-ion diffusivity and cyclability of FCTOS can be improved by expanding the lattice constant and volume change acceptability, respectively.

EIS investigation was performed (see Figure 6A) to measure the electrochemical characteristics of the MXene, MXene-FCTO, and MXene-FCTOS electrodes. Generally, the Nyquist plot is categorised into a highfrequency region (circular arc area) and a low-frequency region (inclined line area).²⁹ The diameter of the arc indicates the resistance (R_{ct}), which corresponds to the interfacial characteristic between the anode and the electrolyte. Among the electrodes, the MXene-FCTOS electrode exhibited the smallest arc diameter, which can be attributed to a low charge transfer resistance. Furthermore, the F and Co dopants induce an increment in the electrical conductivity of MXene-FCTOS, which can provide extra charge carriers and promote electron mobility. Moreover, the MXene-FCTOS electrode exhibited the steepest slope at the low-frequency region, implying a high ionic diffusion kinetic. The result led to an enhanced Li-ion diffusivity due to the enlarged 2D MXene sheet spacing distance and expanded lattice constant with the S dopant. Figure 6B shows the Warburg



FIGURE 6 (A) Nyquist plots, (B) Warburg impedance curve of Z' vs $\omega^{-1/2}$, and (C) ionic diffusion coefficients obtained from MXene, MXene-FCTO, and MXene-FCTOS electrodes



FIGURE 7 (A) Cycling stability and coulombic efficiency measurement at a current density of 100 mA/g for 100 cycles, (B) rate performance at current densities of 100 to 3000 mA/g, and (C) long-term cycling test at a high current density of 2000 mA/g up to 500 cycles of MXene, MXene-FCTO, and MXene-FCTOS electrodes, respectively

impedance coefficients (σ_w) obtained from the slope of the Nyquist plot of MXene, MXene-FCTO, and MXene-FCTOS electrodes.

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$$Z_R = \sigma_w \omega^{-1/2} + R_{\rm ct} + R_e \tag{1}$$

$$D = (\mathrm{RT})^2 / 2\mathrm{A} \left(n^2 F^2 C \sigma_w \right)^2 \tag{2}$$

The ionic diffusion coefficients (D) of all the electrodes were computed using Equations (1) and (2).³⁰ Accordingly, the MXene-FCTOS electrode exhibited a superior diffusion coefficient of 5.56×10^{-13} cm²/s ionic

 $(1.31 \times 10^{-13} \text{ and } 3.05 \times 10^{-13} \text{ cm}^2/\text{s}$ for MXene, and MXene-FCTO electrode, respectively). The outcomes support the fact that the MXene-FCTO electrode exhibits superior electrical conductivity with high Li-ion kinetic property, which directly affects the ultrafast Li-ion storage performance of the LIB anode.³¹

Figure 7A illustrates the cyclability and coulombic efficiency of the electrodes up to 100 cycles for an applied current density of 100 mA/g. All the electrodes exhibit high cyclability up to the 100th cycle owing to the stable MXene framework. Initially, the specific capacity rapidly decreases for a few cycles owing to the solid-electrolyte interphase layer formation during the lithiation process.

After 100 cycles, the MXene-FCTOS electrode exhibited a superior specific capacity of ~365.63 mAh/g (119.17 mAh/g for MXene electrode and 296.21 mAh/g for MXene-FCTOS electrode) and an excellent cycle retention rate of 80.1% (57.7% for MXene electrode and 74.0% for MXene-FCTO electrode, respectively). It is primarily owing to the well-developed ternary-doped tin dioxide hybrid structure with the MXene framework. Moreover, the galvanic charge/discharge curves of the electrodes are shown in Figure S4, to confirm the detailed electrochemical behaviour, corresponding to the 1st, 2nd, 5th, 10th, and 50th charge/discharge reactions of the respective electrodes. In addition, Figure 7B shows the specific capacities at current densities of 100, 300, 700, 1000, 1500, 2000, and 3000 mA/g, respectively to demonstrate the high-rate Li-ion storage performance and the rate capability of the electrodes. The specific capacity of MXene-FCTO20, MXene-FCTO40, and MXene-FCTO60 electrodes were also evaluated. Accordingly, MXene-FCTO20 exhibited the lowest energy storage performance owing to the insufficient loading amount of FCTO. Meanwhile, MXene-FCTO60 also exhibited a lower specific capacity than MXene-FCTO40 owing to the excessive FCTO loading quantity, which blocked the internal diffusion path of the hybrid structure (see Figure S5). In particular, the MXene-FCTOS electrode exhibited a superior energy storage capability under ultrafast reaction conditions (125.25 mAh/g at a current density of 3000 mA/g) than the MXene (38.76 mAh/g) and MXene-FCTOS (60.74 mAh/g) electrodes. The facilitated electrical property of F and Co-doped tin dioxide and the improved ionic diffusivity owing to the increased 2D MXene sheet spacing distance and the expanded lattice constant with the S dopant caused the increased ultrafast energy storage capability. Table S1 summarises the comparison of Li-ion storage capabilities of various anode materials, previously reported with Ti-based MXene composite anode materials.^{5,32-39} Evidently, compared with other composite materials, the MXene-FCTOS electrode exhibited superior Li-ion storage capability under ultrafast charging/discharging conditions. Figure 7C illustrates the long-term cyclability under the ultrafast reaction condition of (current density of 2000 mA/g) up to 500 cycles for investigating the high-rate energy storage capability. The MXene-FCTOS electrode exhibited a superior specific capacity of 157.24 mAh/g. The excellent long-term cyclability of the MXene-FCTOS electrode was attributed to the Co-dopant, which has the capacity to improve the structural stability of tin dioxide during electrochemical reactions.

This study investigated the $Ti_3C_2T_x$ MXene-FCTOS using the USPD process followed by the dopantevaporation method. Accordingly, the MXene-FCTOS ENERGY RESEARCH -WILEY

electrode exhibited a superior energy storage capability at both low and high current density with stable ultrafast cyclability compared to MXene and MXene-FCTO electrodes. These results were primarily attributed to the following effects: (a) generation of extra charge carriers with high electron mobility owing to the high ultrafast energy storage capability of the F and Co dopants of tin dioxide, (b) high specific capacity for the increased 2D MXene sheet spacing due to the growth of FCTOS and the expanded lattice constant of tin dioxide from the S dopant, and (c) excellent ultrafast cyclability for enhanced structural stability of tin dioxide during the electrochemical reaction owing to the Co dopant.

CONCLUSION 4

In this study, the Ti₃C₂T_x MXene-FCTOS were examined for an ultrafast and stable LIB anode. Excellent energy storage performance was accomplished with the synergistic effect of F, S, and Co dopants by constructing an MXene-FCTOS hybrid structure, particularly under the ultrafast reaction condition. During the dopant-evaporation, the growth of the FCTOS particles increased the interlayer distance between the MXene sheets and the S dopant, which expanded the lattice constant of tin dioxide. Accordingly, the MXene-FCTOS electrode demonstrated superior energy storage performance, such as excellent specific capacity (473.24 mAh/g at a current density of 100 mA/g), superior ultrafast Li-ion capability (125.25 mAh/g at a current density of 3000 mA/g), and an excellent ultrafast cyclability of 85.4% after 500 cycles at 2000 mA/g. The results were principally contributed by the (a) high ultrafast energy storage capability for the F and Co dopants of tin dioxide, which enabled high electrical conductivity, (b) high specific capacity for the increased 2D MXene sheet spacing and the expanded lattice constant from the S dopant, and (c) excellent ultrafast cyclability for enhanced structural stability of tin dioxide from the Co dopant. Therefore, the suggested MXene-FCTO could serve as a competitive anode material for ultrafast LIB applications. Moreover, based on the results of this work, synergistic effects of a multi-doped anode material with a hybrid structure were demonstrated, providing a potential strategy for developing ultrafast and stable anode materials in the future.

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DATA AVAILABILITY STATEMENT

Data available in article supplementary material

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