Electrostatic Self-assembly of 0D–2D SnO$_2$ Quantum Dots/Ti$_3$C$_2$T$_x$ MXene Hybrids as Anode for Lithium-Ion Batteries

Huan Liu$^1$, Xin Zhang$^2$, Yifan Zhu$^2$, Bin Cao$^2$, Qizhen Zhu$^2$, Peng Zhang$^2$, Bin Xu$^2$, Feng Wu$^1$, Renjie Chen$^1$

Huan Liu and Xin Zhang have contributed equally to this work.

Bin Xu, binxumail@163.com; Renjie Chen, chenrj@bit.edu.cn

$^1$ School of Materials Science and Engineering, Beijing Key Laboratory of Environmental Science and Engineering, Beijing Institute of Technology, Beijing 100081, People’s Republic of China

$^2$ State Key Laboratory of Organic-Inorganic Composites, Beijing Key Laboratory of Electrochemical Process and Technology for Materials, Beijing University of Chemical Technology, Beijing 100029, People’s Republic of China

HIGHLIGHTS

- 0D–2D SnO$_2$ quantum dots/MXene (SnO$_2$ QDs/MXene) hybrids were synthesized by electrostatic self-assembly.
- MXene not only provides efficient pathways for fast transport of electrons and Li ions, but also buffers the volume change of SnO$_2$ during charge/discharge process.
- The 0D–2D SnO$_2$ QDs/MXene hybrids deliver high capacity, excellent cycle and rate performances as anode of lithium-ion batteries.

ABSTRACT MXenes, a new family of two-dimensional (2D) materials with excellent electronic conductivity and hydrophilicity, have shown distinctive advantages as a highly conductive matrix material for lithium-ion battery anodes. Herein, a facile electrostatic self-assembly of SnO$_2$ quantum dots (QDs) on Ti$_3$C$_2$T$_x$ MXene sheets is proposed. The as-prepared SnO$_2$/MXene hybrids have a unique 0D–2D structure, in which the 0D SnO$_2$ QDs (~4.7 nm) are uniformly distributed over 2D Ti$_3$C$_2$T$_x$ MXene sheets with controllable loading amount. The SnO$_2$ QDs serve as a high capacity provider and the "spacer" to prevent the MXene sheets from restacking; the highly conductive Ti$_3$C$_2$T$_x$ MXene can not only provide efficient pathways for fast transport of electrons and Li ions, but also buffer the volume change of SnO$_2$ during lithiation/delithiation by confining SnO$_2$ QDs between the MXene nanosheets. Therefore, the 0D–2D SnO$_2$ QDs/MXene hybrids deliver superior lithium storage properties with high capacity (887.4 mAh g$^{-1}$ at 50 mA g$^{-1}$), stable cycle performance (659.8 mAh g$^{-1}$ at 100 mA g$^{-1}$ after 100 cycles with a capacity retention of 91%) and excellent rate performance (364 mAh g$^{-1}$ at 3 A g$^{-1}$), making it a promising anode material for lithium-ion batteries.

KEYWORDS MXene; SnO$_2$; Quantum dots; 0D–2D hybrid; Lithium-ion battery
1 Introduction

Lithium-ion batteries (LIBs) are widely used in various portable electronics, electric tools, and electric vehicles due to their high energy density, long cycle life, and environmentally friendly [1, 2]. Nevertheless, the conventional graphite anode of LIBs with a specific capacity of 372 mAh g⁻¹ can hardly meet the rapidly increasing demand of high energy density. Great efforts have been made to develop promising anode materials with high capacity, such as transition metal oxides [3, 4], alloys [5, 6], metal oxides/sulfates [7–9], and phosphorous [10–12]. Among various metal oxides, SnO₂ has attracted a lot of attention due to its relatively high theoretical capacity (790 mAh g⁻¹, which is twice than the currently used graphite), low average working potential (~0.6 V vs. Li⁺/Li), natural abundance and low price [13–16]. Unfortunately, its practical application as anode material in LIBs is seriously limited by the poor cycle stability resulting from the severe volume change (> 300 vol%) during the charge/discharge process. Meanwhile, SnO₂ also suffers from low electrical conductivity, resulting in poor rate capability. To improve the electrochemical performances of SnO₂, several strategies have been proposed to overcome these issues. One of the effective way is to fabricate nanostructured SnO₂, such as SnO₂ quantum dots (QDs) [17], SnO₂ hollow spheres [18], or SnO₂ nanowires [19], which could restrain the structure changes during lithium alloying and shorten the ion diffusion lengths [20]. The other way is to combine SnO₂ with various carbon materials possessing high conductivity such as carbon nanotubes, carbon fiber or graphene [21–26]. The conductive carbon can not only improve the overall electrical conductivity of the composites but also act as a buffer to slow down the structure collapse of the electrode. 

MXenes are a newly emerging family of 2D materials with a general formula of $M_{n+1}X_nT_x$, where $M$ represents early transition metal (M=Ti, Sr, V, Cr, Ta, Nb, Zr, Mo, and Hf), X is carbon and/or nitrogen, and T stands for the surface termination groups (–OH, –F=O) [27–31]. Due to their excellent electrical conductivity, tailorable surface chemistries, and mechanical properties, MXenes have recently attracted great interests in energy storage devices such as LIBs, sodium-ion batteries, and supercapacitors [32–35]. Particularly, as one of the most widely studied MXenes, Ti₃C₂Tₓ is a potential anode material for LIBs, which can deliver excellent cycle stability and superior rate performances. However, the theoretical reversible capacity of Ti₃C₂Tₓ is only 320 mAh g⁻¹ [36]. On the other hand, MXene can also be used as a substrate to fabricate hybrids with other active materials, including metal oxides, which have higher theoretical capacity but poor conductivity and are prone to large volume change during charge/discharge. In the hybrids, MXene can improve the conductivity and buffer the volume changes of the metal oxide, while the metal oxide provides high capacity. Thus, the MXene/metal oxide hybrid could achieve high capacity, stable cycle and good rate performance [37–41]. For example, Ti₃C₂Tₓ/Fe₂O₃ nanocomposite was prepared by confining Fe₂O₃ nanoparticles into Ti₃C₂Tₓ nanosheets through ball-milling method, which showed reversible capacities of ~203 mAh g⁻¹ at 1 C and 100 mAh g⁻¹ at 10 C [37]. MXene/NiCo₂O₄ composite with a capacity reaching up to 1330 mAh g⁻¹ was synthesized by spray coating method [38]. Some recent works indicate that MXene is also a good substrate to improve the lithium storage performance of SnO₂. The hybrids of SnO₂ with MXene prepared by wet hydrothermal approach has shown a high capacity of 1021 mAh g⁻¹ and improved cycle stability [40]. However, a few reports indicate that MXene is unavoidable to be oxidized to titanium dioxide (TiO₂) as a by-product during these processes, thereby, influencing the electrochemical performance of the composites. Recently, our group proposed a general route to self-assemble transition metal oxide nanostructures on Ti₃C₂Tₓ MXene nanosheets through van der Waals interaction. The proposed method allowed fabrication of hybrids without getting MXene to be oxidized and achieved enhanced cycle and rate performance [15].

In this work, a simple method is proposed to prepare 0D–2D SnO₂ QDs/MXene hybrids by electrostatic self-assembling SnO₂ QDs on the surface of 2D Ti₃C₂Tₓ MXene nanosheets under ultrasonication. Since, the synthesis is accomplished in a very mild condition, i.e., ultrasonication treatment of the mixture of negatively charged MXene and positively charged SnO₂ QDs at room temperature, the MXene oxidation is effectively avoided. In the hybrids, 2D nanosheet of MXene acts as a substrate to support 0D SnO₂ QDs, which can not only provide large electrode/electrolyte interface area for fast reversible transport of electrons and ions, but could also inhibit the aggregation of SnO₂ QDs and buffer the volume changes during charge/discharge process. The SnO₂ QDs with ultra-small particle size can effectively maximize the activity and specific capacity and minimize
the volume change while inhibiting the structure collapse during charge/discharge process and shortening the lithium diffusion pathways. In addition, the SnO₂ QDs acts as a “spacer” to prevent the MXene nanosheets from restacking and thus protecting the Li⁺ migration channels and active sites. These unique features endow the 0D–2D SnO₂ QDs/MXene hybrids with high lithium storage capacity, excellent cycle stability and superior rate performance, indicating a promising anode for LIBs.

2 Experimental

2.1 Synthesis of Ti₃C₂Tₓ MXene

The Ti₃C₂Tₓ MXene was synthesized by etching Ti₃AlC₂ (400 mesh, purchased from Yiyi Technology Co., Ltd.) with LiF + HCl solution as reported previously [41]. Typically, 1.0 g Ti₃AlC₂ powder was subjected to a mixture containing LiF (1.0 g) and hydrochloric acid (12 M, 10 mL) under stirring conditions for 24 h at 35 °C. After several times of centrifugation-washing with deionized (DI) water, the product was then dispersed in 50 mL DI water, stored under ultrasound for 30 min. The dark green supernatant was collected by centrifugation at 3500 rpm for 1 h. Finally, the black MXene liquid was obtained and sealed for future use.

2.2 Synthesis of SnO₂ QDs

In order to obtain SnO₂ QDs, 4 mmol SnCl₂·2H₂O and 4 mmol thiourea (CH₄N₂S) were added to 30 mL DI water and magnetically stirred at room temperature to form a milky suspension. After stirring for 24 h, a clear yellow aqueous solution containing SnO₂ QDs was obtained.

2.3 Synthesis of 0D–2D SnO₂ QDs/MXene Hybrids

In a typical synthesis, 5 mL of as-prepared SnO₂ QDs solution was added to 40 mg 0.1 mg mL⁻¹ Ti₃C₂Tₓ MXene solution under ultrasonication for 6 h. The SnO₂ QDs were deposited on the Ti₃C₂Tₓ layers during this process and solid–liquid separation was observed. Finally, the black precipitate of SnO₂ QDs/MXene hybrids were collected by vacuum filtration, washed with water and dried in a vacuum oven at 80 °C for 6 h. The above hybrid was denoted as SnO₂ QDs/MXene-52. For comparison, we also prepared another SnO₂ QDs/Ti₃C₂Tₓ hybrids (SnO₂ QDs/MXene-51) under the same conditions, but the addition amount of MXene in this solution was 20 mg.

2.4 Materials Characterization

Scanning electron microscopy (SEM) characterization was conducted using a Gemini SEM 500. Transmission electron microscopy (TEM) characterization was conducted on a JEOL JEM-F200 (HR) equipped with selected area electron diffraction (SAED). X-ray diffraction (XRD) patterns were recorded on a Bruker D8 ADVANCE with monochromatic Cu Kα radiation (λ = 1.54060 Å). Raman spectra were obtained with a LabRAM HR Evolution Raman spectrometer (633 nm). X-ray photoelectron spectroscopy (XPS) analysis was performed using a Thermo Fisher ESCALAB Xi⁺ to analyze the chemical compositions of the samples.

2.5 Electrochemical Measurements

The working electrodes were prepared by mixing 80 wt% active material, 10 wt% Super P and 10 wt% carboxymethylated cellulose (CMC) in DI water. After coating the slurry on the copper foil, the electrodes were dried at 60 °C in vacuum oven for 8 h to remove the solvent. To test electrochemical performances, CR2025-type coin cells were assembled in an argon-filled glove box (Mikrouna, H₂O, O₂ < 0.1 ppm) using Li foil as half-cell counter electrode, and microporous membrane (Celgard 2400) as separator. The electrolyte was 1 M LiPF₆ in a mixture of ethylene carbonate (EC)/diethyl carbonate (DEC)/dimethyl carbonate (DMC) with a volume ratio of 1:1:1. The charge/discharge (GCD) tests were performed using a LAND BT2000 battery tester. The potential window was 0.01–2.5 V versus Li/Li⁺. The CV traces were recorded on a CS350 electrochemical workstation from 0.01 to 2.5 V. Electrochemical impedance spectroscopy (EIS) measurements were performed on the VSP Bio-Logic SAS at frequencies ranging from 10 mHz to 100 kHz with an applied AC signal amplitude of 10 mV. The capacities of the samples were calculated based on all the components in the active materials, i.e., the mass of SnO₂ QDs/Ti₃C₂Tₓ hybrids.
3 Results and Discussion

The synthesis route for 0D–2D SnO$_2$ QDs/MXene by electrostatic self-assembly is illustrated in Fig. 1. Firstly, transparent yellow aqueous solution of positively charged SnO$_2$ QDs is prepared by hydrolysis, dehydration and oxidation of SnCl$_2$·2H$_2$O in DI water, where thiourea is added as a promoter and stabilizer (Fig. S1a). The mercaptan group can easily bind to Sn$^{2+}$, and the SnO$_2$ QDs whose zeta potential is $+99.0$ mV (Fig. S1b) is surrounded by a positively charged protic amino group (–NH$_3^+$), which makes it highly stable and electropositive [42]. The Ti$_3$C$_2$T$_x$ MXene solution with its negatively charged groups (–F, –OH) [43], and zeta potential of $-36.2$ mV, is very stable in water (Fig. S1a) due to the hydrophilicity and electrostatic repulsion between neighboring nanosheets. When positively charged SnO$_2$ QDs are added into the negatively charged Ti$_3$C$_2$T$_x$ colloidal solution, the SnO$_2$ QDs can easily load onto the surface of the MXene nanosheets. After the continuous ultrasonication of 6 h, the supernatant becomes clear and colorless, and black precipitates are obtained. The positively charged SnO$_2$ QDs are captured by the negatively charged MXene nanosheets only by ultrasonic treatment without other components and additional treatments, implying an electrostatic self-assembly mechanism for the designed 0D–2D SnO$_2$ QDs/MXene hybrids. The Ti$_3$C$_2$T$_x$ MXene with 2D layered structure as a conductive matrix facilitates the charge transfer and accommodates the volume change of SnO$_2$ QDs; the SnO$_2$ QDs thus prevents the MXene nanosheets from restacking by working as “spacer” and providing channels for fast transfer of Li ion with promising electrochemical performance.

SEM and TEM were employed to characterize the morphology and structure of the as-prepared samples. The pure Ti$_3$C$_2$T$_x$ (Fig. S1c) displays a compact 2D layered structure. After decoration with SnO$_2$ QDs, the SnO$_2$ QDs/MXene hybrids exhibit 0D–2D structure, as shown in Fig. 2a. From

![Fig. 1 Schematic illustration for the preparation of 0D–2D SnO$_2$ QDs/MXene hybrids](Image)

![Fig. 2 a SEM image, b TEM image, c HRTEM image of 0D–2D SnO$_2$ QDs/MXene hybrid. d SAED patterns of SnO$_2$ QDs. e STEM image and corresponding elemental mapping images of Ti, C, Sn, and O](Image)
a closer view in Fig. 2b, it can be seen that the spatially dispersed SnO2 QDs are evenly distributed over the surface of the MXene nanosheets. The particle-size distribution analysis (Fig. S1d) indicates the SnO2 QDs have an average particle size of ~4.5 nm, favoring the electrode/electrolyte interactions. Since the diffusion of Li ions is strongly dependent on the transport length and the active sites, the ultra-small particle size of SnO2 QDs can not only expose a large number of electrochemical active sites shuttling Li ions in and out, but also shorten the diffusion path of Li ion transport, which are beneficial for improving the capacity and rate performance. Figure 2c shows clear lattice fringes of the SnO2 QDs, indicating a high degree of crystallinity. The crystal lattice with a spacing of 0.33 nm is consistent with the d spacing of (110) planes of the SnO2 tetragonal phase. The selected area electron diffraction (SAED) pattern (Fig. 2d) shows clear diffraction rings, implying the polycrystalline nature of SnO2. These diffraction rings can be well indexed to the (110), (101), and (211) planes of SnO2. Moreover, the typical scanning TEM (STEM) and elemental mapping images of SnO2 QDs/MXene hybrid (Fig. 2e) show homogeneously distributed Ti, C, Sn, and O elements, demonstrating the uniform loading of SnO2 QDs on the surface of MXene sheets.

The phase structures of the as-prepared SnO2 QDs/MXene hybrids were verified by XRD as shown in Fig. 3a. Ti3C2T x exhibits the major peaks, such as the (002), (006), (008), (0010), and (0012) [44]. Typically, the (002) plane of the Ti3C2T x MXene is located at 2θ = 6.4°, corresponding to an interplanar spacing of 13.7 Å [45]. In addition, the pure tetragonal phase of crystalline SnO2 (JCPDS No. 41-1445) is located at 26.5°, 34.1°, and 52.4°, corresponding to (110), (101), and (211). The XRD patterns of the SnO2 QDs/MXene hybrids consist of Ti3C2T x and tetragonal phase SnO2, indicating that SnO2 QDs/MXene hybrids have successfully formed. No any extra crystalline phase peaks such as TiO2 are observed, indicating the electrostatic self-assembly process is mild with no oxidation of MXene. In addition, the (002) peak of the SnO2–MXene composite (Fig. S1b) was downshifted compared to pure MXene, indicating increased interlayer spacing of the MXene in the hybrids.

Raman spectra further confirm the phase characteristics of the SnO2 QDs/MXene-52 hybrid. As shown in Figs. 3b and S1f, the peaks of pure SnO2 at 271, 465, and 698 cm⁻¹ can be assigned to the E g and A 1g active mode of SnO2, respectively [46]. Moreover, the pure MXene exhibits a peak at 199 cm⁻¹ which corresponds to the A 1g symmetry out-of-plane vibrations of Ti atoms, whereas the peaks at 381 and 622 cm⁻¹ are related to the E g group vibrations, including in-plane (shear) modes of Ti, C, and surface functional group atoms [47]. For the SnO2 QDs/MXene-52, the spectrum manifests six cognizable Raman-active modes, combining the characteristic Raman peaks of Ti3C2Tx and SnO2. In comparison with the pure SnO2, the peak intensity of SnO2 in the hybrid has significantly declined. This suggests that the SnO2 QDs are well separated by the Ti3C2Tx nanosheets, which weakens the Raman signal from the SnO2. It’s worth noting that no strong peak for TiO2 was detected at 144 cm⁻¹, confirming that MXene has not oxidized during the hybrid formation.

The elemental composition of SnO2 QDs/MXene hybrid was further analyzed by XPS. For pristine Ti3C2Tx MXene, there are only four main elements, Ti, C, F, and O, whereas for SnO2 QDs/MXene-52, the Sn element is also detected, indicating the presence of SnO2 in the hybrid (Fig. S2a). In the high-resolution C 1s spectrum (Fig. 3c), the characteristic peaks correspond to C–Ti (284.2 eV), C–C (288.7 eV), C–O (288.1 eV), C=O (289.5 eV), and O–C=O (291.6 eV) [48]. The particular peak located at 282.1 eV can be assigned to the C–Ti bond in Ti3C2Tx sheets. The XPS spectrum of the Ti 2p (Fig. 3d) reveals that peaks of Ti bound to C, Ti(II), and Ti(III). The Ti–C 2p3/2, Ti(II) 2p3/2, Ti(III) 2p3/2, T–C 2p1/2, Ti(II) 2p1/2, and Ti(III) 2p1/2 peaks are detected at binding energies of 455.1, 455.6, 456.8, 458.8, 461.3, and 462.3 eV, respectively. After loading the SnO2 QDs, no Ti(IV) peak is observed, suggesting no oxidation of MXene in the SnO2 QDs/MXene-52 (Fig. 3f). Meanwhile, the XPS in Sn 3d region has two peaks at 487.2 and 495.6 eV, which are attributed to Sn 3dx2−y2 and Sn 3dz2 of SnO2, confirming the formation of SnO2 (Fig. S2b). Besides this, the relative intensities of Ti–C, Ti(II), and Ti(III) peaks in SnO2 QDs/MXene-52 are relatively weaker than pure Ti3C2Tx, indicating decreasing Ti3C2Tx signal for the hybrid. Furthermore, the slight shift of the Ti–C component to lower binding energy indicates that the synthesis of SnO2 QDs/MXene hybrid by electrostatic attraction might have caused shift in the electron density (Fig. 3e). All of these observations demonstrate that SnO2 QDs have been successfully deposited on the surface of the Ti3C2Tx sheets. In addition, the introduction of SnO2 QDs on the Ti3C2Tx surface increases the accessible surface area [49], which is evident from the nitrogen adsorption measurements (Fig. S2c). The SnO2 QDs/MXene-52 shows a typical type I adsorption/desorption
isotherms with a BET specific surface area of 184 m² g⁻¹, much higher than that of the pure MXene (19 m² g⁻¹). The large surface area is beneficial for accelerating electrolyte diffusion and accommodating volume change of the SnO₂ QDs during charge/discharge. Thus, much improved lithium storage performances could be expected.

To evaluate the electrochemical performances of the SnO₂ QDs/MXene hybrids as anode materials in LIBs, coin-type half cells were assembled using lithium as counter electrode. CV curves of Ti₃C₂Tex MXene and SnO₂ QDs/MXene hybrids were scanned between 0.01 and 2.5 V. For the pure Ti₃C₂Tₓ MXene, the broad irreversible reduction peak at around 0.7 V is observed in the first lithiation process, which is attributed to the formation of a solid electrolyte interphase (SEI) generated from the reaction of Ti₃C₂Tₓ with Li⁺ [17]. In the subsequent cycles, the reversible peaks near 0.77 and 1.5 V may be the consequence of the reaction between Li⁺ and the titanium-based compounds (Fig. S3a) [50]. For the pure SnO₂ QDs (Fig. S3b), the SnO₂ is considered to transform into LiₓSn (x ≤ 4.4) and Li₂O during the initial discharge process (lithium insertion). The cathodic peak at 0.05 V result from the alloying process of Sn to LiₓSn (0 ≤ x ≤ 4.4), and the strong anode peak at about 0.5 V is caused by the de-alloying process of LiₓSn (0 ≤ x ≤ 4.4).
The anode peak at 1.2 V is caused by the partial reversible transformation of Sn to SnO\textsubscript{2} owing to its quantum size [51, 52]. However, in the second and third cycles of the pure SnO\textsubscript{2}, the intensities of the cathodic and anodic peaks show continuous and significant decline, indicating rapid capacity degradation because of the structural variation of SnO\textsubscript{2} during lithiation/delithiation processes (Fig. S3b). The SnO\textsubscript{2} QDs/MXene-52 (Fig. 4a) shows CV curves with similar characteristic peaks, but the curves in the 2nd and 3rd cycles almost overlap, indicating good cycle performance. In comparison with the SnO\textsubscript{2} QDs/MXene-51 (Fig. 4b), the SnO\textsubscript{2} QDs/MXene-52 display better overlapping CV curves with the same peak positions, implying excellent reversibility in its conversion reaction.

Furthermore, the GCD profiles (Fig. 4c, d) of the SnO\textsubscript{2} QDs/MXene at 50 mA g\textsuperscript{-1} coincides well with the CV curves. The GCD profile of the Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} and SnO\textsubscript{2} QDs electrodes were also tested at the same conditions (Fig. S3c, d). In the initial discharge profile of the SnO\textsubscript{2} QDs/MXene hybrids, the plateaus at 0.7 and 0.05 V correspond to the SEI formation and lithium alloying; while during the initial charge, the plateaus at 0.5 and 1.2 V relate to lithium de-alloying and partial reversible SnO\textsubscript{2} formation, respectively. The reversible capacity of the SnO\textsubscript{2} QDs/MXene-52 is 887.4 mAh g\textsuperscript{-1} in the first cycle, with initial Coulombic efficiency (CE) of about 51.2%. The low CE might have resulted from the SEI and Li\textsubscript{2}O formation as well as the electrolyte decomposition. In the 5th cycle, the capacity was determined to be about 847.6 mAh g\textsuperscript{-1} and the corresponding CE reached about 100%. With the SEI film protection, the capacity reaches a stable state. In contrast, the SnO\textsubscript{2} QDs/MXene-51 delivers an initial reversible capacity of 897.5 mAh g\textsuperscript{-1} with a CE of 43.0% (Fig. 4d). The results indicate that the introduction of more SnO\textsubscript{2} QDs can increase available active sites and the capacity of the hybrid material, but at the same time cause more side reactions and reduce the initial CE, due to its ultra-small particle size and high surface area. Therefore, only appropriate ratio of SnO\textsubscript{2} QDs and MXene sheets could reach an optimum electrochemical performance.

![Fig. 4](image-url) Electrochemical performances as anode in LIBs. a, b CV curves of SnO\textsubscript{2} QDs/MXene at a scan rate of 0.1 mV s\textsuperscript{-1} in 0.01–2.5 V. c, d Charge/discharge curves of SnO\textsubscript{2} QDs/MXene at 50 mA g\textsuperscript{-1}
Figure 5a shows the comparison of the charge/discharge cycle performance among Ti$_3$C$_2$T$_x$ MXene, SnO$_2$ QDs, and SnO$_2$ QDs/MXene at 100 mA g$^{-1}$. The bare Ti$_3$C$_2$T$_x$ MXene has a low initial capacity of 79.2 mAh g$^{-1}$ with a CE of 34.2%, which is attributed to the restacking of MXene nanosheets [36]. The initial capacity of the pure SnO$_2$ QDs can reach 835.9 mAh g$^{-1}$, but it fades very rapidly due to the severe pulverization of SnO$_2$ during charge/discharge. After 20 cycles, the capacity remains only 144.6 mAh g$^{-1}$ with a capacity retention ratio of about 17% of the initial capacity. In contrast, by electrostatic self-assembly of the SnO$_2$ QDs on the 2D Ti$_3$C$_2$T$_x$ MXene nanosheets, the SnO$_2$ QDs/MXene hybrids exhibit much enhanced cycle stability. The capacity of SnO$_2$ QDs/MXene-52 reaches to 659.8 mAh g$^{-1}$ with 91% retention of the initial capacity after 100 cycles, which is much higher than that of the pure SnO$_2$ QDs and Ti$_3$C$_2$T$_x$ MXene. In a comparative evaluation of SnO$_2$ QDs/MXene hybrids with different SnO$_2$/MXene ratio, it is found that the SnO$_2$ QDs/MXene-52 with abundant MXene shows better cycle stability than the SnO$_2$ QDs/MXene-51, indicating the importance of adequate MXene substrate in achieving optimum performance [53].

Another attractive feature of the SnO$_2$ QDs/MXene electrodes is the excellent rate performance. As shown in Fig. 5b,
the SnO₂ QDs/MXene electrode exhibit much enhanced rate capability compared to pure SnO₂ QDs. Especially for SnO₂ QDs/MXene-52, as the current density increases from 50 to 100, 200, 500, 1000, 2000, and 3000 mA g⁻¹, its reversible capacity remains 887.4, 655.2, 584.5, 522.0, 454.7, 409.7, and 364.0 mAh g⁻¹, respectively, demonstrating superior rate performance. When the current density returns back to 50 mA g⁻¹ again, the capacity recovers to 688.1 mAh g⁻¹. These results indicate that the unique 0D–2D architecture of the SnO₂ QDs/MXene hybrids facilitates the Li ion diffusion and the electron transfer, thereby enhancing the reaction kinetics and the rate capability. The comparison of the rate performance for QDs/MXene-52 with previously reported SnO₂-based anodes and other MXene-based anodes is plotted in Fig. 5c. The SnO₂ QDs/MXene-52 demonstrate superior rate capability compared to other anode materials based on MXene matrix, such as SnO₂ QDs/MXene backbone [40], SnO₂ nanosheets/MXene [54], Fe₃O₄/MXene [37], Fe₃O₄ nanoparticles@MXene [50], TiO₂ nanowire/Ti₃C₂ [55], CoO nanoparticles/Ti₃C₂ [44], MoS₂/p-Ti₃C₂ [56], and Si/Ti₃C₂ [57] etc.

Electrochemical impedance spectroscopy was employed to compare the reaction kinetics of the SnO₂ QDs/MXene-52 and the bare SnO₂ QDs. The typical Nyquist plots of the two electrodes (Fig. 5d) consist of a compressed semicircle in the intermediate frequency region and a diagonal line in the low frequency range. The semicircle is related to the charge transfer resistance (Rₑ), and the oblique line is related to Warburg impedance, suggesting the diffusion of Li ion in the active materials [58]. The Rₑ values of the SnO₂ QDs/MXene-52 and SnO₂ QDs electrode were calculated to be 75.50 and 100.20 Ω, respectively. Obviously, SnO₂ QDs/MXene-52 possesses much lower Rₑ value compared to bare SnO₂ QDs. This can be attributed to the high electrical conductivity of the MXene and the fast charge diffusion reaction due to its unique 0D–2D structure. Moreover, the SnO₂ QDs/MXene-52 shows a relatively steep low-frequency tail, indicative of high Li ion diffusibility, which results from the efficient ion transfer pathways constructed by MXene.

The above excellent electrochemical performances are because of the synergic effect between MXene nanosheets and SnO₂ QDs, and the mechanism is illustrated in Fig. 5e. In the SnO₂ QDs/MXene hybrids, the MXene nanosheets act as 2D substrates for uniform anchoring of SnO₂ QDs. The MXene nanosheets prevent the aggregation of SnO₂ QDs and work as an elastic buffer space to adapt to the volume expansion/contraction of SnO₂ QDs during charging and discharging, thus leading to good cycle stability. Furthermore, MXene nanosheets with good electric conductivity construct effective conductive channels for SnO₂ QDs, facilitating fast charge transport and improving the rate performance. Moreover, the unique 0D–2D structure offers massive electrochemically active sites for high specific capacity, which contribute in improving the electrochemical performance of electrode materials, thus excellent lithium-ion storage performances are obtained for SnO₂ QDs/MXene hybrids.

4 Conclusions

The 0D–2D SnO₂ QDs/MXene hybrids have been successfully synthesized by an efficient electrostatic self-assembly strategy. The 0D SnO₂ QDs with an average size of 4.7 nm are uniformly distributed on the 2D MXene nanosheets with strong adhesion, acting as structurally stable host for lithium storage. The 2D MXene nanosheets buffer the volume change of SnO₂ QDs during charge/discharge and construct effective channels for charge transport. Besides this, the 0D–2D structure creates additional active sites. The 2D conductive Ti₃C₂Tx MXene, ultra-small SnO₂ QDs, and unique 0D–2D nanoarchitecture are synergistically responsible for the outstanding electrochemical performances of the SnO₂ QDs/MXene hybrids. As an anode for LIBs, it exhibits a high specific capacity of 887.4 mAh g⁻¹ at 50 mA g⁻¹, excellent rate capability (364 mAh g⁻¹ at 3 A g⁻¹), and superior cycle stability (659.8 mAh g⁻¹ after 100 cycles with 91% retention). These results indicate that the 0D–2D SnO₂ QDs/MXene is a promising anode material for advanced LIBs. In addition, the electrostatic self-assembly method could be extended to other transition metal oxide/MXene hybrids and will have potential applications in sodium-ion batteries, potassium-ion batteries, and supercapacitors.

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