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## Nanoscopically and uniformly distributed $\text{SnO}_2@\text{TiO}_2/\text{C}$ composite with highly mesoporous structure and biochemical bonds for enhanced lithium ion storage performances<sup>†</sup>

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The ultralow volume deformation (<4%) and low cost have aroused great interest in using  $\text{TiO}_2$  as the anode of lithium ion batteries (LIBs), but its low capacity (168 mA h g<sup>-1</sup>), no more than half of the theoretical capacity, limits its practical application in high-energy-density LIBs. In order to solve this problem, here we propose a one-step method for fabrication of the  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanocomposite, which features a superior nanoarchitecture with mesopores, interfacial chemical bonds, vast phase boundaries, carbon coating, and ultrasmall nanocrystals. These nanostructures endow  $\text{SnO}_2@\text{TiO}_2/\text{C}$  with a high capacity of 830.7 mA h g<sup>-1</sup> at 0.5C after 100 cycles, excellent cyclability over 1000 cycles with negligible capacity loss per cycle (0.004%) at 10C, and a high lithium ion transport rate within a few seconds for one cycle. Importantly, the full cell with prelithiated  $\text{SnO}_2@\text{TiO}_2/\text{C}$  as the anode and commercial  $\text{LiCoO}_2$  as the cathode achieves a high energy density of 328.4 W h kg<sup>-1</sup> at 0.1C and 245.9 W h kg<sup>-1</sup> at 1C, which are superior to those of previously reported  $\text{TiO}_2$ -based materials.

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## Introduction

Titanium dioxide ( $\text{TiO}_2$ ) has been regarded as a promising anode material in rechargeable lithium ion batteries (LIBs) due to its low cost, non-toxicity, and ultralow volume change (<4%) during lithium ion intercalation/deintercalation.<sup>1,2</sup>  $\text{TiO}_2$  possesses a series of allotropes, such as anatase,<sup>3,4</sup> rutile,<sup>5,6</sup> and  $\text{TiO}_2\text{-B}$ .<sup>7,8</sup> Among them, anatase  $\text{TiO}_2$  has been widely investigated due to its inherent crystal structure for lithium ion storage.<sup>9,10</sup> However, the low theoretical capacity (168 mA h g<sup>-1</sup>) corresponding to the formula of  $\text{Li}_{0.5}\text{TiO}_2$  of anatase  $\text{TiO}_2$  cannot meet the ever-increasing demand of high-energy-density LIBs, thus limiting its practical use.<sup>3</sup> In order to enhance the capacity of  $\text{TiO}_2$ , a large number of efforts have been made: (i) preparing nanostructures like nanoparticles,<sup>3</sup> nanotubes,<sup>4</sup> nanosheets,<sup>11</sup> and nanomembranes;<sup>12</sup> (ii) fabricating mesoporous composites;<sup>13,14</sup> (iii) forming phase boundaries;<sup>11</sup> and (iv) constructing interfacial chemical bonds.<sup>1,15</sup> Specifically, the design of nanostructures and mesoporous structure is intended to increase the contact area of

active material with the electrolyte and shorten the transport distance of lithium ions, thus ensuring sufficient reaction between lithium ions and the active material to increase the reversible capacity. Additionally, the capacity can be enhanced by diminishing the particle size to the nanoscale, which can increase the number of interfaces between materials to accommodate more lithium ions.<sup>16,17</sup> Similarly, introducing multi-phase compounds can increase the capacity by generating numerous phase boundaries to provide additional lithium ion storage sites.<sup>11</sup> Furthermore, the formation of chemical bonds between multiple phases can create a strong interfacial force, which can not only enhance the structural stability of the active material and achieve high capacity retention, but also can enhance the capacity by increasing the diffusion depth of lithium and enabling more active materials to react with lithium ions.<sup>1,15</sup> Accordingly, a  $\text{TiO}_2$ -based anode with these structures can be assumed to deliver satisfactory capacity. Thus far, several  $\text{TiO}_2$ -based anode materials with similar structures have been reported. For example, anatase  $\text{TiO}_2$  nanoparticles with mesoporous structure prepared by atomic layer deposition based on a sacrificial carbon template were shown to have a capacity of 158.4 mA h g<sup>-1</sup> with a capacity retention of 80% after 100 cycles at 1C and a rate capability of 105 mA h g<sup>-1</sup> at 5C.<sup>3</sup> Additionally, a nanocomposite with ultrathin anatase  $\text{TiO}_2$  nanosheets embedded into  $\text{TiO}_2\text{-B}$  nanodomains and vast phase boundaries formed within them was also reported to enhance the lithium ion storage capacity, with a specific capacity of 280 mA h g<sup>-1</sup> at 0.5C and 190 mA h g<sup>-1</sup> after 1000 cycles and a

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capacity retention of 86% at 10C.<sup>11</sup> Moreover, a TiO<sub>2</sub>/graphene nanocomposite with strong Ti–O–C chemical bonds in the interfaces synthesized by a hydrothermal reaction exhibited a capacity of 206.7 mA h g<sup>-1</sup> at 3C and 140.3 mA h g<sup>-1</sup> after 100 cycles and a capacity retention of 87.7% at 30C.<sup>18</sup> Furthermore, a high capacity of 227.2–274.0 mA h g<sup>-1</sup> with good cyclability and rate performance during 200–800 cycles at a current density of 10C or lower was obtained by a TiO<sub>2</sub>@C nanocomposite prepared by a hydrothermal reaction followed by carbonization<sup>13</sup> and a TiO<sub>2</sub>@reduced graphene oxide nanocomposite synthesized by aerosol-assisted spray drying followed by calcination.<sup>19</sup>

Despite the improved lithium ion storage capacity, the above-mentioned TiO<sub>2</sub>-based nanocomposites are still low in capacity at various current densities. Besides, the synthesis steps of these nanocomposites were complex, involving sonicating, stirring, centrifuging, washing, drying, calcinating, and etching, coupled with some repeated operations, suggesting the necessity of a simple fabrication route for preparing high-capacity TiO<sub>2</sub>-based nanocomposites with the above-mentioned structures (i–iv) to promote their practical application.

Herein, we propose a one-step method for fabricating a highly mesoporous SnO<sub>2</sub>@TiO<sub>2</sub>/C nanocomposite with SnO<sub>2</sub> nanocrystals homogeneously dispersed in the TiO<sub>2</sub>/C matrix and an average size of about 10 nm. The coexistence of multiple phases in the nanocomposites induces numerous phase boundaries and thus the formation of Sn–O–C and Ti–O–C chemical bonds. The addition of high-capacity SnO<sub>2</sub> (13.0 wt%), coupled with these structural advantages, endows the SnO<sub>2</sub>@TiO<sub>2</sub>/C nanocomposite with a reversible capacity of 830.7 mA h g<sup>-1</sup> after 100 cycles at 0.5C, higher than any of the reported TiO<sub>2</sub>-based anodes at a similar cycle number and current density. Furthermore, SnO<sub>2</sub>@TiO<sub>2</sub>/C is also shown to deliver excellent cyclability and rate performance in half and full cells.

## Experimental

### Materials

Tetrabutyl orthotitanate tetramer (C<sub>40</sub>H<sub>90</sub>O<sub>13</sub>Ti<sub>4</sub>, 99.9%, TOT) and monobutyltin oxide (C<sub>4</sub>H<sub>10</sub>O<sub>2</sub>Sn, 99.9%, MO) were purchased from Tokyo Chemical Industry (Tokyo, Japan); the electrolyte (1 M LiPF<sub>6</sub> in a mixture of ethylene carbonate/diethylene carbonate/dimethyl carbonate at a volume ratio of 1:1:1) from DoDoChem; acetylene black, Li foil, Cu foil, Al foil, polyvinylidene fluoride (PVDF), the Celgard 2400 membrane, *n*-methyl-2-pyrrolidone (NMP), and lithium cobaltate (LiCoO<sub>2</sub>) from MTI Corporation; and the stabilized lithium metal power (SLMP) from FMC Lithium Co.

### Preparation of TiO<sub>2</sub>/C and SnO<sub>2</sub>@TiO<sub>2</sub>/C

The precursor solution was obtained by dissolving 0.2 g MO in 1 g TOT, then transferring the solution into a reaction vessel and sealing it in a glove box under an argon environment. SnO<sub>2</sub>@TiO<sub>2</sub>/C was prepared by heating the vessel to 600 °C at 10 °C min<sup>-1</sup>, maintaining it for 0.5 h in a tube furnace with flowing Ar, and then cooling to room temperature naturally.

Meanwhile, TiO<sub>2</sub>/C was synthesized by heating pure 1 g TOT under the same conditions.

### Characterization

The morphology, structure, and composition of the obtained samples were characterized using a scanning electron microscope (SEM, Hitachi S-4700), transmission electron microscope (TEM, FEI Talos F200x) with an X-ray energy dispersive spectrometer (EDS), accelerated surface area and porosimetry system (Micromeritics ASAP 2010), X-ray diffractometer (XRD, D/max-2500/PC, Rigaku), Raman spectrometer (Renishaw RM-1000), X-ray photoelectron spectrometer (XPS, Thermo Scientific Escalab 250Xi), thermogravimetric analyzer (TGA, STA449 F3 Jupiter), and inductively coupled plasma atomic emission spectrometer (ICP-AES). The electrical conductivity of the samples was tested with a powder electrical resistivity tester (ST-2722, Suzhou Jingge Electronic Co., Ltd, China).

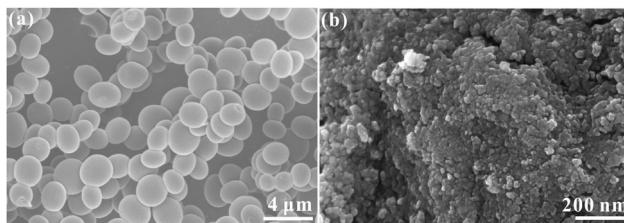
### Electrochemical measurements

The electrodes were prepared by coating a mixture of active materials, acetylene black, and PVDF at a weight ratio of 8:1:1 on Cu foil, followed by drying at 80 °C for 12 h in a vacuum oven. The mass of active material loaded on each electrode was about 1.2 mg cm<sup>-2</sup>. The electrochemical performances were measured *via* assembling a 2032 coin-type cell in a glove box filled with pure argon, which consisted of the prepared electrode, Li foil, a Celgard 2400 membrane, and the electrolyte. The electrochemical performances of the cells were measured on a Land CT2001A battery-test system (Wuhan Land Electronic Co., China) in the voltage range of 0.01–3.00 V (vs. Li/Li<sup>+</sup>) and at current densities of 1–50C (1C = 168 mA g<sup>-1</sup>). The electrochemical impedance spectra (EIS) were measured in the frequency range of 10<sup>5</sup> to 10<sup>-2</sup> Hz with an amplitude of 5 mV, and the cyclic voltammogram (CV) in the voltage range of 0.01 to 3.00 V (vs. Li/Li<sup>+</sup>) at scanning rates of 0.1–10 mV s<sup>-1</sup> on a CHI 760D electrochemical workstation (Shanghai CH Instruments Co., China). In the full cell, the cathode electrode consisted of LiCoO<sub>2</sub> (90 wt%), PVDF (5 wt%), and acetylene black (5 wt%) on Al foil, and the N/P ratio was 1.1 at a mass loading of 2.0 and 10.5 mg cm<sup>-2</sup> for SnO<sub>2</sub>@TiO<sub>2</sub>/C and LiCoO<sub>2</sub>, respectively. Before assembling the coin-type full cell, the SnO<sub>2</sub>@TiO<sub>2</sub>/C electrode was pre-lithiated by using the commercial SLMP to improve its first coulombic efficiency (CE). The specific process has been reported in our previous report.<sup>15</sup> For full-cell testing, the cycling curves were measured at 0.1C (1C = 0.14 A g<sup>-1</sup>) and rate curves were tested at 0.2–1C in the voltage window of 1.0–3.6 V. All cells were tested at room temperature.

## Results and discussion

Fig. 1 shows the SEM images of TiO<sub>2</sub>/C. In Fig. 1a, TiO<sub>2</sub>/C exhibits a spherical shape with an average size of 2.5 μm due to the high vapor pressure, with its formation mechanism being discussed in detail in our previous reports.<sup>20,21</sup> Interestingly, adding MO into TOT led to the formation of nanoparticles with



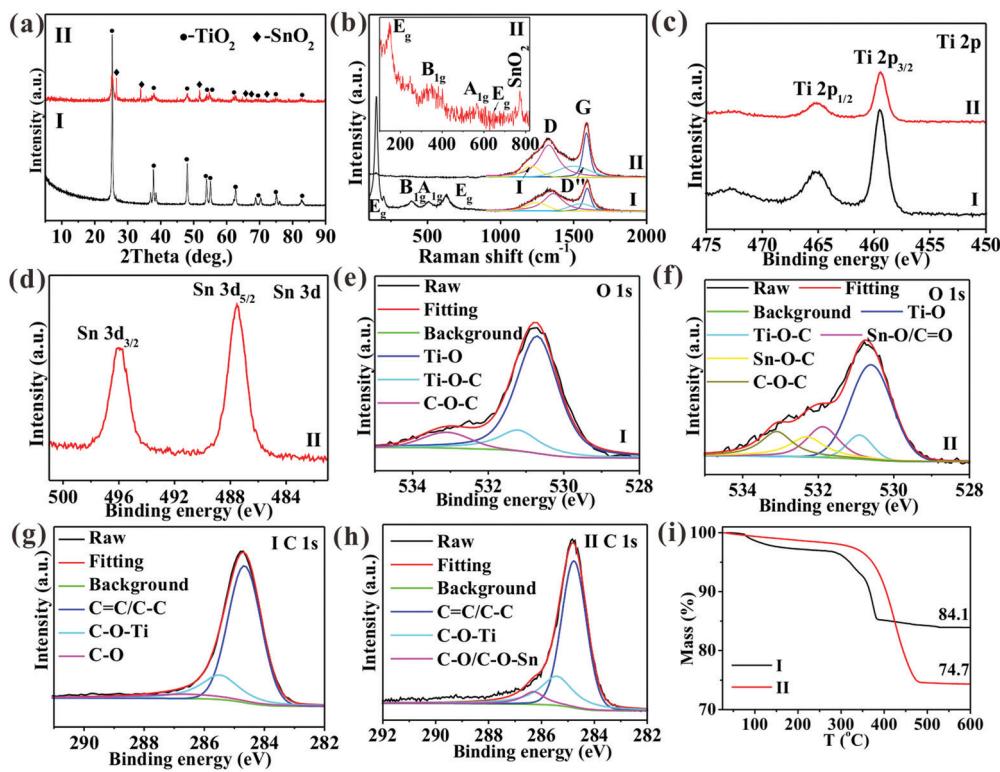
Fig. 1 SEM images of  $\text{TiO}_2/\text{C}$  (a) and  $\text{SnO}_2@\text{TiO}_2/\text{C}$  (b).

an average size of 15 nm (Fig. 1b), indicating that MO addition facilitates nanocomposite formation in the vapor pressure-induced reaction process.<sup>15</sup>

In the XRD patterns (Fig. 2a), the two samples show diffraction peaks at 25.3, 37.8, 48.1, 53.9, 54.9, 62.6, 68.7, 75.1, and 82.7°, corresponding, respectively, to the (101), (004), (200), (105), (211), (204), (116), (215), and (224) crystal planes of anatase  $\text{TiO}_2$  (JCPDS: 21-1272), suggesting the successful synthesis of anatase  $\text{TiO}_2$ . Besides,  $\text{SnO}_2@\text{TiO}_2/\text{C}$  exhibits four peaks at 26.6, 33.8, 51.8, and 66.1°, corresponding, respectively, to the (110), (101), (211), and (301) crystal planes of crystalline  $\text{SnO}_2$  (JCPDS No. 41-1445), indicating the formation of  $\text{SnO}_2$ . In the Raman spectra with the insert for the enlarged image of  $\text{SnO}_2@\text{TiO}_2/\text{C}$  in the range of 100–835  $\text{cm}^{-1}$  (Fig. 2b), the two samples show obvious Raman peaks of anatase  $\text{TiO}_2$  at around 148.7, 392.4, 506.6, and 630.9  $\text{cm}^{-1}$  (Fig. 2b), corresponding to the  $E_g$ ,  $B_{1g}$ ,  $A_{1g}$ , and  $E_g$  modes,<sup>3,12</sup> as well as two peaks around 1323.8 and 1590.5  $\text{cm}^{-1}$ , corresponding to the D and G peaks of carbon materials,<sup>15,22,23</sup>

respectively, indicating the existence of anatase  $\text{TiO}_2$  and free carbon. Obviously,  $\text{SnO}_2@\text{TiO}_2/\text{C}$  exhibits the Raman peak of  $\text{SnO}_2$  at about 770  $\text{cm}^{-1}$ , suggesting the presence of  $\text{SnO}_2$  in the sample. Meanwhile, the D peak arises from a double resonance process involving a phonon and a defect, while the G peak is attributed to in-plane vibrations and  $E_{2g}$  symmetry. Due to the overlap of the D and G peaks, peak fitting was performed, and additional peaks appeared at about 1240 and 1500  $\text{cm}^{-1}$ , labeled as I and D'', respectively. The I peak is related to disorder in the graphitic lattice or  $\text{sp}^2$ – $\text{sp}^3$  bonds,<sup>22,23</sup> while the D'' peak is known to occur in the presence of amorphous carbon.<sup>22,23</sup> Besides, the intensity ratios of the D and G ( $I_D/I_G$ ) peaks indicate the disorder degree of the graphitic structure,<sup>22,23</sup> which are close to each other for the two samples (0.68 for  $\text{SnO}_2@\text{TiO}_2/\text{C}$  and 0.67 for  $\text{TiO}_2/\text{C}$ ), suggesting a similar disorder degree for the carbon in both of them. Furthermore, the high ratio of  $I_D/I_G$  indicates the existence of vast defects in the carbon, which favors lithium ion storage.

The contents of the elements in the precursor and the two samples are shown in Table S1, ESI.† The obtained samples are seen to retain the elements of the precursor apart from H. Furthermore, compared with the precursor, the obtained samples show an increase in the mass percentages of Ti and Sn elements while a decrease in the mass percentages of C and H. These results suggest that a large number of C,H-containing substances were produced by the decomposition of the precursors at a high temperature, which could not be converted into solids under high pressure, leading to a decrease in the mass of C and H.

Fig. 2 (a) XRD, (b) Raman spectra, (c–h) XPS spectra of  $\text{Ti} 2\text{p}$  (c),  $\text{Sn} 3\text{d}$  (d),  $\text{O} 1\text{s}$  (e and f), and  $\text{C} 1\text{s}$  (g and h), and (i) TG curves of  $\text{TiO}_2/\text{C}$  (I) and  $\text{SnO}_2@\text{TiO}_2/\text{C}$  (II).

According to the XPS results (Fig. S1, ESI<sup>†</sup>), the atomic ratio of O and Ti is around 2.11, approaching the theoretical value of  $\text{TiO}_2$ , and the atomic ratio of O and Sn is about 2.02, close to the theoretical value of  $\text{SnO}_2$ , indicating the formation of  $\text{TiO}_2$  and  $\text{SnO}_2$ . Additionally, the two samples show two XPS peaks around 465.2 and 459.4 eV due to the binding energies of  $\text{Ti} 2p_{3/2}$  and  $\text{Ti} 2p_{1/2}$  of anatase  $\text{TiO}_2$ ,<sup>1,3</sup> respectively (Fig. 2c), further suggesting the formation of anatase  $\text{TiO}_2$ . The  $\text{SnO}_2@ \text{TiO}_2/\text{C}$  samples exhibit two Sn 3d peaks of  $\text{Sn}^{4+} 3d_{3/2}/3d_{5/2}$  at around 495.9/487.5 eV (Fig. 2d), again indicating the formation of  $\text{SnO}_2$ .<sup>24,25</sup> The two samples also show a wide peak of O 1s from 528.8 to 534.4 eV, which can be fitted using five peaks (Fig. 2e and f): Ti–O bonds at 530.7 eV,<sup>26,27</sup> Ti–O–C bonds at 531.2 eV,<sup>26,27</sup> Sn–O/C=O at 531.5 eV,<sup>28</sup> Sn–O–C at 532.3 eV,<sup>28</sup> and C–O–C at 533.1 eV,<sup>26,28</sup> confirming the formation of Ti–O–C and Sn–O–C bonds. The C 1s peaks of the two samples are fitted using three peaks (Fig. 2g and h): C=C/C–C at 284.8 eV,<sup>22</sup> Ti–O–C at 285.4 eV,<sup>26,29</sup> and C–O/C–O–Sn at 286.2 eV,<sup>30</sup> further confirming the formation of the Ti–O–C and Sn–O–C bonds. The percentage of Ti–O–C bonds increases from 20.7 for  $\text{TiO}_2/\text{C}$  to 25.5% for  $\text{SnO}_2@ \text{TiO}_2/\text{C}$  (Table S2, ESI<sup>†</sup>), due to the production of more interfaces between  $\text{TiO}_2$  and C by the smaller-sized  $\text{TiO}_2$  nanoparticles in  $\text{SnO}_2@ \text{TiO}_2/\text{C}$ . Additionally, the Sn–O–C bonds increase from 0 to 4.1% with the addition of MO into TOT (Table S2, ESI<sup>†</sup>). The high content of Ti–O–C and Sn–O–C bonds favors lithium ion storage. Since the XPS technique can only detect the surface (several nanometers) composition of the material, the XPS spectra of  $\text{SnO}_2@ \text{TiO}_2/\text{C}$  in the deeper area were also tested to further confirm the presence of chemical bonds of Ti–O–C and Sn–O–C bonds inside the sample. Briefly, the sample powders were compressed into a thin plate, followed by bombarding it with argon ions for 30 min, and testing the bombarded area by XPS. The XPS results (Fig. S2, ESI<sup>†</sup>) are consistent with the data in Fig. 2c–h, indicating that the

chemical bonds of Ti–O–C and Sn–O–C are distributed in the whole  $\text{SnO}_2@ \text{TiO}_2/\text{C}$  sample. ICP-AES results reveal the mass percentages of Sn/Ti as 0/50.3 and 10.2/36.8 wt%, indicating that the mass contents of  $\text{SnO}_2/\text{TiO}_2/\text{C}$  are 0/83.9/16.1 wt% and 13.0/61.3/25.7 wt%, corresponding to  $\text{TiO}_2/\text{C}$  and  $\text{SnO}_2@ \text{TiO}_2/\text{C}$ , respectively (Table S3, ESI<sup>†</sup>). The TG curves (Fig. 2i) show that the mass percentages of the residuals post high temperature oxidation are 84.1 and 74.7%, corresponding to  $\text{TiO}_2/\text{C}$  and  $\text{SnO}_2@ \text{TiO}_2/\text{C}$ , respectively, suggesting that the respective carbon content is 15.9 and 25.3 wt%, which are consistent with the ICP-AES results.

Fig. 3 shows the high angle annular dark field (HAADF) image and its corresponding EDS mapping images. Ti, O, and C elements are seen to be uniformly distributed on the surface of  $\text{TiO}_2/\text{C}$  spheres (Fig. 3a–d). The average size of  $\text{TiO}_2$  particles in the  $\text{TiO}_2/\text{C}$  spheres is shown to be about 45 nm by measuring the crushed powder, with a decrease of 10 nm in the size of the nanoparticles after adding MO into TOT (Fig. 3f), which agrees with the SEM observation (Fig. 1b). In Fig. 3g, carbon layers can be seen at the edge of the sample, confirming the presence of the carbon coating. Fig. 3h shows the lattice fringes of the (101) crystal plane of anatase  $\text{TiO}_2$  and (110) crystal plane of  $\text{SnO}_2$ , corresponding, respectively, to the highest diffraction peaks of  $\text{TiO}_2$  at 25.3° and  $\text{SnO}_2$  at 26.6° (Fig. 2a). Besides, it can be clearly observed that the nanocrystals are well interconnected by C, combined with the existence of vast chemical bonds of Ti–O–C and Sn–O–C, suggesting that the nanocomposite possesses the superior nanoarchitecture of C/C–O–Ti/ $\text{TiO}_2$ /Ti–O–C/C–O–Sn/ $\text{SnO}_2$ /Sn–O–C/C. In Fig. 3i, the selected area electron diffraction (SAED) pattern shows the Debye–Scherrer ring patterns of the (101), (004) and (211) crystal planes of anatase  $\text{TiO}_2$  as well as the (110) and (221) crystal planes of  $\text{SnO}_2$ , further confirming the existence of  $\text{TiO}_2$  and  $\text{SnO}_2$  nanocrystals. In Fig. 3j–n, HAADF and its corresponding EDS elemental mapping images show the even

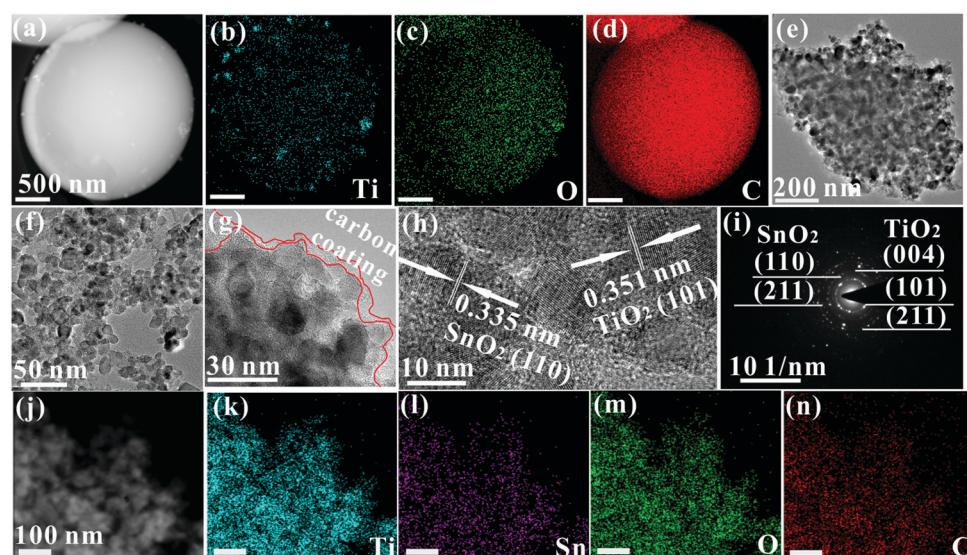


Fig. 3 (a) High angle annular dark field image and the corresponding EDS elemental mapping images of Ti (b), O (c), and C (d) of  $\text{TiO}_2/\text{C}$  spheres; (e) TEM image of crushed  $\text{TiO}_2/\text{C}$  spheres; (f) TEM image, (g and h) HRTEM image, and (i) the corresponding SAED pattern of  $\text{SnO}_2@ \text{TiO}_2/\text{C}$ ; and (j) HAADF image and the corresponding EDS elemental mapping images of Ti (k), Sn (l), O (m), and C (n) of  $\text{SnO}_2@ \text{TiO}_2/\text{C}$ .



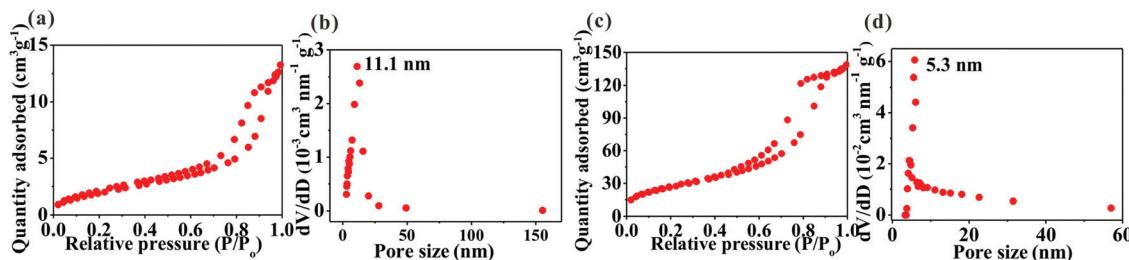


Fig. 4 Nitrogen adsorption–desorption isotherms and pore-size distribution of TiO<sub>2</sub>/C (a and b) and SnO<sub>2</sub>@TiO<sub>2</sub>/C (c and d).

distribution of Ti, Sn, O, and C elements, verifying the homogeneous dispersion of TiO<sub>2</sub>, SnO<sub>2</sub>, and free carbon in the nanocomposite. The homogeneous dispersion structure at the nanoscale could induce numerous phase boundaries or interfaces, contributing to lithium ion storage.

Fig. 4 shows the Brunauer–Emmett–Teller (BET) surface area and Barrett–Joyner–Halenda (BJH) pore-size distribution of the samples determined by nitrogen adsorption–desorption isotherms. The two samples exhibit a typical type-IV isotherm, indicating that they possess a mesoporous structure. Due to the formation of nanostructure, SnO<sub>2</sub>@TiO<sub>2</sub>/C has a significantly higher value than TiO<sub>2</sub>/C in the BET surface area (143.3 m<sup>2</sup> g<sup>-1</sup> versus 11.8 m<sup>2</sup> g<sup>-1</sup>) and pore volume (0.86 cm<sup>3</sup> g<sup>-1</sup> versus 0.06 cm<sup>3</sup> g<sup>-1</sup>), with mesopores centered at 5.3 nm for the former and 11.1 nm for the latter. Comparatively, the disadvantage of the highly mesoporous structure of the SnO<sub>2</sub>@TiO<sub>2</sub>/C nanocomposite involves the increase of the active material specific surface area, contributing to the formation of more solid electrolyte interface (SEI) film during the first cycle and decreasing the first coulombic efficiency (CE). However, this disadvantage can be improved by the commercial prelithiation technique.<sup>15</sup> Accordingly, the low CE of our SnO<sub>2</sub>@TiO<sub>2</sub>/C anode is not an obstacle to its practical application. More importantly, the porous structure possesses several advantages: (i) favoring the contact of the active material with the electrolyte; (ii) shortening the diffusion distance of Li<sup>+</sup>; (iii) facilitating the storage of additional Li<sup>+</sup>; and

(iv) accommodating the volume change of the active material upon cycling, thus leading to enhanced capacity, cycling life, and rate performance.<sup>13,14</sup> Collectively, the preparation of a porous structure is favorable for lithium ion storage.

Fig. 5 shows the charge/discharge and cycling curves of the two samples. Different from the first charge/discharge curve of TiO<sub>2</sub>/C, SnO<sub>2</sub>@TiO<sub>2</sub>/C exhibits two potential plateaus below 0.6 V in the charge/discharge curves, attributed to the delithiation/lithiation of SnO<sub>2</sub>.<sup>21,31</sup> Additionally, SnO<sub>2</sub>@TiO<sub>2</sub>/C does not show obvious delithiation plateaus of anatase TiO<sub>2</sub> at 2.15 V, probably due to the contribution of SnO<sub>2</sub> and higher carbon content.<sup>15</sup> The reversible capacity of the active material has been reported to be associated with the relative content of each component, the particle size, and the number of phase boundaries and chemical bonds at the interface.<sup>15,21</sup> Due to low theoretical capacity of anatase TiO<sub>2</sub>, adding high-capacity active material can greatly enhance the capacity of TiO<sub>2</sub>-based anodes, such as SnO<sub>2</sub> and amorphous carbon. Owing to the low electrical conductivity (EC) of anatase TiO<sub>2</sub>, adding materials with higher EC can considerably improve the electrical connectivity of the whole electrode, enabling more active materials to react with lithium ions and thus increasing the specific capacity.<sup>21</sup> The EC is shown to increase with a rise in the carbon content (Table S4, ESI†). As previously reported, active materials with a nanoscale size possess higher specific capacity than their corresponding bulk materials, because nano-sized materials can remarkably

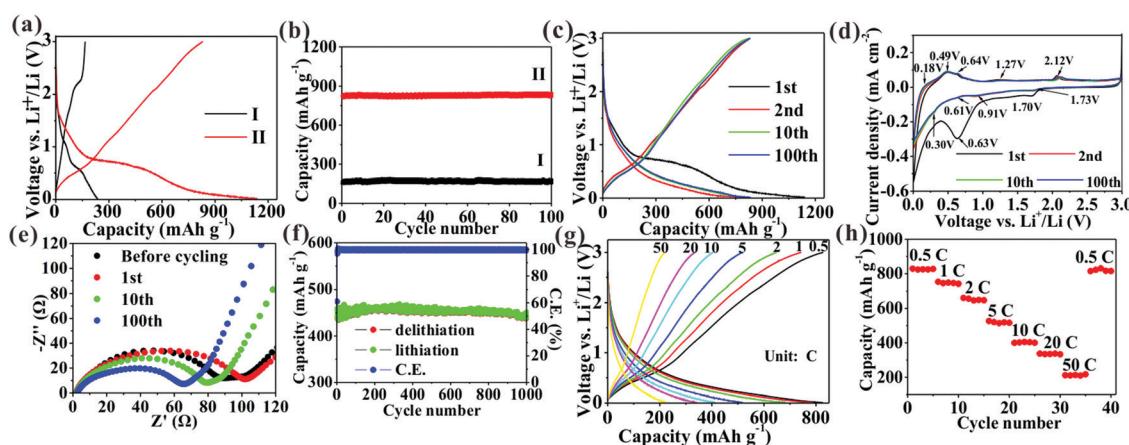


Fig. 5 (a) First charge/discharge curves; (b) cycling curves at 0.5C of TiO<sub>2</sub>/C (I) and SnO<sub>2</sub>@TiO<sub>2</sub>/C (II); (c) charge/discharge curves at different cycles; (d) CV curves; (e) Nyquist plots; (f) cycling performance at 10C; (g) charge/discharge curves at different current densities; and (h) rate performance of SnO<sub>2</sub>@TiO<sub>2</sub>/C.



shorten the lithium ion diffusion distance and achieve deeper lithiation to enhance the capacity.<sup>3,4</sup> Introducing more components into the active materials can generate more phase boundaries to store extra lithium ions and enhance the reversible capacity.<sup>11</sup> The formation of chemical bonds in the interface of each phase can increase the interfacial defects, EC, and structure stability, thus achieving higher capacity and cyclability.<sup>1,15</sup> In Fig. 5b and Table S5, ESI,<sup>†</sup>  $\text{SnO}_2@\text{TiO}_2/\text{C}$  is seen to have a higher specific capacity (830.7  $\text{mA h g}^{-1}$ ) than  $\text{TiO}_2/\text{C}$  (169.6  $\text{mA h g}^{-1}$ ) after 100 cycles due to its larger amount of  $\text{SnO}_2$ , C, Sn–O–C, and Ti–O–C bonds as well as higher EC (Tables S2–S4, ESI<sup>†</sup>).

The electrochemical performance of  $\text{SnO}_2@\text{TiO}_2/\text{C}$  was further investigated. Fig. 5c shows its voltage profiles at different cycle numbers. The first discharge and charge capacities are 1141.2 and 823.4  $\text{mA h g}^{-1}$ , respectively, with a first CE of 72.2%. The low CE has been reported to arise from the formation of an SEI layer and  $\text{Li}_2\text{O}$ .<sup>15,21</sup> The subsequent charge/discharge curves retain a similar shape, indicating the high stability of the electrode structure during cycling. After 100 cycles, a high reversible capacity of 830.7  $\text{mA h g}^{-1}$  is observed, corresponding to a capacity retention of 100.9%. The increased post-cycling capacity may result from interfacial  $\text{Li}^+$  storage and electrochemical activation.<sup>15</sup> In the present study, the obtained reversible capacity (830.7  $\text{mA h g}^{-1}$ ) is higher than that of any previously reported  $\text{TiO}_2$ -based anode (Table S6, ESI<sup>†</sup>), due to the formation of a large number of phase boundaries, chemical bonds, and mesoporous sites in the nanocomposite, facilitating the storage of more lithium ions and thus increasing the capacity.<sup>1,11,13</sup> Additionally, adding a high amount of  $\text{SnO}_2$  and C also contributes to the enhancement of the capacity, leading to a high reversible capacity of 1419.5  $\text{mA h g}^{-1}$  for the  $\text{SnO}_2/\text{C}$  nanocomposite (Fig. S3, ESI<sup>†</sup>). Fig. 5d shows the CV curves of  $\text{SnO}_2@\text{TiO}_2/\text{C}$ , with the presence of the characteristic anodic peaks at about 2.12 V and cathodic peaks at about 1.73 V of anatase  $\text{TiO}_2$ .<sup>9,10</sup> Besides, the three anodic peaks and two cathodic peaks below 0.7 V belong to the delithiation and lithiation behaviors of  $\text{SnO}_2$ , respectively.<sup>21,31</sup> Interestingly, the presence of a pair of oxidation and reduction peaks at 1.27 and 0.91 V is not the typical delithiation/lithiation behavior of  $\text{TiO}_2$ ,  $\text{SnO}_2$ , or C, which may be attributed to the formation of a new reversible lithium ion storage site by phase boundaries, defects, interfacial chemical bonds, and the mesoporous structure. Fig. 5e shows the Nyquist plots at different cycle numbers. The EIS were fitted to an equivalent circuit (Fig. S4, ESI<sup>†</sup>), where  $R_s$  is the electrolyte resistance, corresponding to the intersection of

the high-frequency oblique line and the horizontal axis;<sup>32</sup>  $R_{ct}$ , the charge transfer resistance, corresponding to the diameter of the depressed semicircle;<sup>32</sup> and  $W$ , the Warburg impedance of  $\text{Li}^+$  ion diffusion, corresponding to the low-frequency slope line.<sup>32</sup> The values of  $R_s$  and  $R_{ct}$  at different cycle numbers are shown in Table S7, ESI,<sup>†</sup> With a rise in the cycle number, the  $R_s$  value is shown to gradually increase, suggesting the increase of the electrolyte resistance with increasing cycling number. Meanwhile, the  $R_{ct}$  value is seen to increase after the 1st cycle due to the formation of an SEI layer, followed by a gradual decrease, probably due to electrochemical activation on cycling.<sup>15</sup> The decrease of  $R_{ct}$  favors the enhancement of the capacity and cyclability. In Fig. 5f, a long cycling life is shown at 10C, with a high specific capacity of 438.5  $\text{mA h g}^{-1}$  at a 0.004% capacity loss per cycle after 1000 cycles as well as an average CE of 99.72% during 2–1000 cycles, indicating the high reversibility of the electrode during cycling. The lithium ion transport of  $\text{SnO}_2@\text{TiO}_2/\text{C}$  was investigated by measuring the rate capability at current densities of 0.5 to 50C (Fig. 5g and h), and the shape of the charge/discharge curves remains unchanged at different current densities, indicating that the electrode structure is stable during rate testing. The rate capacities are measured as 827.4, 742.2, 647.8, 516.8, 400.6, 333.5, and 217.7  $\text{mA h g}^{-1}$  at 0.5, 1, 2, 5, 10, 20, and 50C, respectively, with a high capacity of 217.7  $\text{mA h g}^{-1}$  at 50C, sufficiently proving the excellent rate performance of  $\text{SnO}_2@\text{TiO}_2/\text{C}$ . Importantly, the specific capacity returns to almost 100% of the initial capacity with the current density back to 0.5C, confirming that the electrode structure is still highly stable even after high current charging and discharging. Our  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanocomposite is superior to other  $\text{TiO}_2$ -based anodes in cycling and rate performances (Table S6, ESI<sup>†</sup>). Especially, the rate capability is comparable and even superior to that of other anodes, such as a Sn-based anode, a  $\text{SiO}_x/\text{SiO}_y$  membrane, a Si nanotube,  $\text{Nb}_{18}\text{W}_{16}\text{O}_{93}$ , a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  nanowire, and a graphite/Si/carbon composite (Table S8, ESI<sup>†</sup>).

The reasons for the high capacity of  $\text{SnO}_2@\text{TiO}_2/\text{C}$  are further explored by estimating the pseudocapacitance contribution in the total capacity using CV curves at different scanning rates (Fig. 6a). The relationship between the scanning rate ( $v$ ) and peak current ( $i_p$ ) satisfies the following eqn (1):

$$\log(i_p) = a \log(v) + \log(b) \quad (1)$$

where  $a$  and  $b$  are empirical parameters. The 0.5  $a$ -value indicates a diffusion-controlled behavior and the 1  $a$ -value represents an ideal pseudocapacitive behavior. The  $a$ -value can be calculated

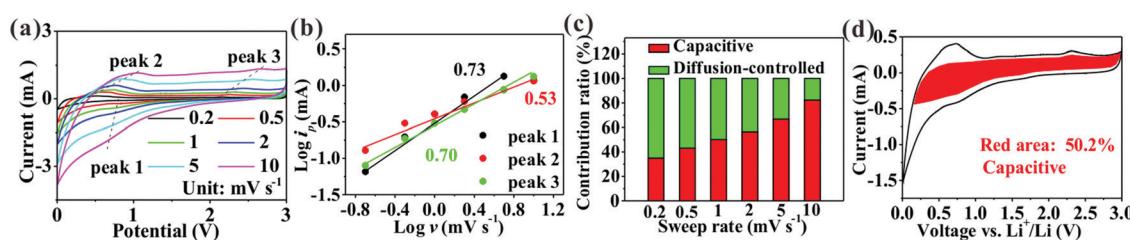


Fig. 6 (a) CV curves at different scanning rates; (b) the line relationship of  $\log(i_p)$  vs.  $\log(v)$  at peaks 1–3 marked in (a); (c) the percentages of the pseudocapacitive contribution at different scanning rates; and (d) the detailed pseudocapacitive contribution at a scanning rate of 1  $\text{mV s}^{-1}$  of  $\text{SnO}_2@\text{TiO}_2/\text{C}$ .



as the slope from the plots of  $\log(i)$  versus  $\log(v)$  at peaks 1–3 (Fig. 6b). The  $\alpha$ -value for peak 1, peak 2, and peak 3 is calculated as 0.51, 0.53, and 0.70, respectively (Fig. 6b), indicating that the diffusion-controlled and pseudocapacitive behaviors are responsible for the high capacity of  $\text{SnO}_2@\text{TiO}_2/\text{C}$ . The relationship of the total capacity at a given  $v$  and voltage (V) is shown in the following eqn (2):

$$i(\text{V}) = k_1 v^{1/2} + k_2 v \quad (2)$$

where the values of  $k_1 v^{1/2}$  and  $k_2 v$  represent the diffusion-controlled and pseudocapacitive process, respectively. An increase of  $v$  from 0.2 to 10  $\text{mV s}^{-1}$  witnesses an increase from 35.1 to 82.3% in the percentage of the pseudocapacitive contribution (Fig. 6c), suggesting the significant role of pseudocapacitive behavior in the total capacity, especially at a high  $v$ . The specific pseudocapacitive contribution at a scanning rate of 1  $\text{mV s}^{-1}$  is presented in the red area (Fig. 6d). The high pseudocapacitive contribution in the  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanocomposite can be attributed to the following three reasons: (i) vast phase boundaries between  $\text{TiO}_2$ ,  $\text{SnO}_2$ , and  $\text{C}$  can offer extra  $\text{Li}^+$  storage sites; (ii) the formation of a large number of interfacial chemical bonds can induce numerous defects as additional  $\text{Li}^+$  storage sites; and (iii) the mesoporous structure can accommodate excess  $\text{Li}^+$ .

The practicality of the  $\text{SnO}_2@\text{TiO}_2/\text{C}$  anode was confirmed by testing the delivery capacity of a full cell assembled with a prelithiated  $\text{SnO}_2@\text{TiO}_2/\text{C}$  anode and  $\text{LiCoO}_2$  cathode. The full cell exhibits a high capacity of 142.2  $\text{mA h g}^{-1}$ , a capacity retention of 93.3% after 100 cycles at 0.1C (Fig. 7a and b) and a superior rate performance with a capacity of 110.7  $\text{mA h g}^{-1}$  at 1C (Fig. 7c and d), which are higher than the values of the reported full cells of graphite/ $\text{LiCoO}_2$  and graphite/ $\text{LiFePO}_4$ .<sup>33–35</sup> The gravimetric energy density of the full cell can be calculated by the following eqn (3):<sup>36</sup>

$$\text{Energy density (W h kg}^{-1}\text{)} \left( \frac{C_{\text{cathode}} \times m_{\text{cathode}}}{(m_{\text{cathode}} + m_{\text{anode}})} \right) \times V \quad (3)$$

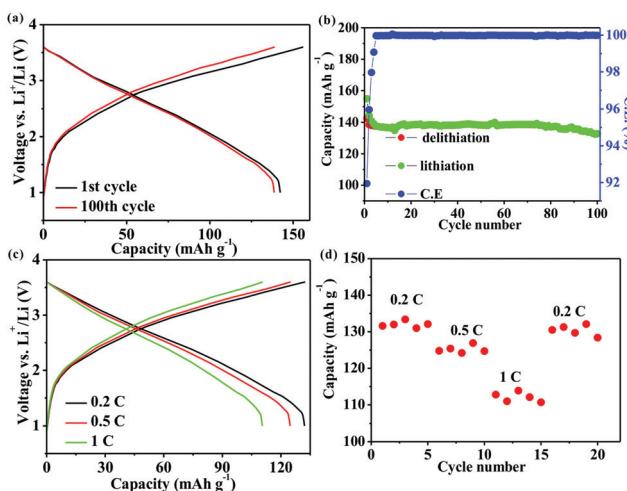


Fig. 7 (a) The charge/discharge curves at 0.1C; (b) the cycling performance at 0.1C; (c) the charge/discharge curves at different current densities; and (d) the rate performance of full cells. The capacity is calculated based on the mass of  $\text{LiCoO}_2$ .

where  $C_{\text{cathode}}$  is the specific capacity calculated based on the mass of the cathode;  $V$ , the nominal voltage of 2.75 V; and  $m_{\text{cathode}}/m_{\text{anode}}$ , the active mass of the cathode and anode, respectively. Accordingly, the gravimetric energy density is calculated as about 328.4  $\text{W h kg}^{-1}$  at 0.1C and 245.9  $\text{W h kg}^{-1}$  at 1C, which is comparable to that of a graphite/ $\text{LiCoO}_2$  full cell (335  $\text{W h kg}^{-1}$  at 0.1C),<sup>37–39</sup> and superior to that of the reported full cell of a  $\text{TiO}_2$ -based anode.<sup>40,41</sup> In previous reports,<sup>41</sup> the nominal voltage is shown as about 2 V in the  $\text{TiO}_2/\text{LiCoO}_2$  full cell. In our case, the enhanced nominal voltage may be ascribed to (i) the addition of low-working potential crystalline  $\text{SnO}_2$  (0.2–0.8 V)<sup>21</sup> and amorphous carbon (below 0.5 V) and (ii) the formation of a new lithium ion storage site, with a pair of oxidation and reduction peaks present, respectively, at 1.27 and 0.91 V, as confirmed by the CV curves. It should be mentioned that the energy density should be calculated based on the mass of the whole cell, including both the active materials (cathode material, Li anode and electrolyte) and the inactive materials (conductive carbon, binder, current collectors, tabs, separator and packaging material). However, our research focuses on improving the capacity of anode materials. For the whole battery, when the areal capacity of the active material is constant, the mass of the anode material tends to decrease with an increase of its capacity, which can improve the energy density of the battery. The mass values of the inactive materials and electrolyte should be a fixed value in batteries, but they are absent in eqn (3), because they are unclear for us. In academic studies, researchers are more inclined to use the simplified eqn (3) to calculate the energy density,<sup>33–36</sup> because it still makes sense in that the higher the energy density calculated by this simplified equation, the higher the energy density when calculated with all materials included, suggesting the reference value of this calculated density.

The high stability of the electrode structure was verified by SEM and TEM analysis of the electrode after 2000 cycles at 10C. In the SEM images, the electrode surface is observed to be intact (Fig. S5a and b, ESI†), without any cracks in the nanoparticles (Fig. S5c and d, ESI†). These results confirm the high structural stability of  $\text{SnO}_2/\text{TiO}_2/\text{C}$  nanocomposites during cycling, which is ascribed to the unique nanoarchitecture of  $\text{SnO}_2@\text{TiO}_2/\text{C}$  (Fig. 8). Specifically, the carbon coating on the surface of  $\text{TiO}_2$  and  $\text{SnO}_2$  nanocrystals can greatly suppress the structural volume change, enhance the electrical conductivity, and inhibit the aggregation of nanocrystals, thus improving the

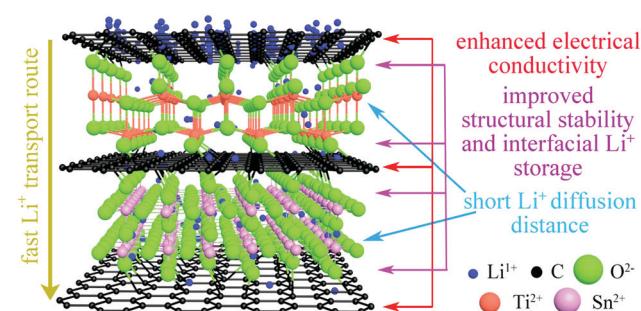


Fig. 8 A schematic illustration of the lithium ion storage mechanism in the  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanoarchitecture.

cyclability and rate performance.<sup>42,43</sup> Additionally, the formation of Ti–O–C and Sn–O–C bonds in the interfaces can promote interfacial charge transfer and enhance the structural stability of  $\text{SnO}_2@\text{TiO}_2/\text{C}$ , thus contributing to fast lithium ion transport and long cycling life.<sup>15</sup> Furthermore, the phase boundaries and mesoporous structure can afford the storage of additional  $\text{Li}^+$  and thus achieve a high capacity.<sup>42,43</sup> Finally, the ultrasmall nanocrystals can supply enormous active storage sites and shorten the  $\text{Li}^+$  diffusion distance, thus facilitating high capacity and enhancing the rate capability.<sup>42,43</sup>

## Conclusion

In this research, we propose a one-step pressure-induced vapor phase method for fabricating a chemically bonded  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanocomposite with a highly mesoporous structure as well as  $\text{SnO}_2$  and  $\text{TiO}_2$  nanocrystals of a size of about 10 nm. The fine multi-component nanocrystals are shown to induce a large amount of phase boundaries, defects, interfacial chemical bonds, and mesoporous structures, endowing the  $\text{SnO}_2@\text{TiO}_2/\text{C}$  nanocomposite with a high reversible capacity of  $830.7 \text{ mA h g}^{-1}$  after 100 cycles at 0.5C,  $438.5 \text{ mA h g}^{-1}$  after 1000 cycles at 10C, and  $217.7 \text{ mA h g}^{-1}$  at 50C in the half cell. In the full cell, a high energy density of 328.4 and  $245.9 \text{ W h kg}^{-1}$  is achieved at 0.1 and 1C, respectively. These lithium ion storage performances are superior to those of previously reported  $\text{TiO}_2$ -based anodes.

## Conflicts of interest

There are no conflicts of interest to declare.

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